A model-based concept for an optimized resin transfer moulding process

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Abstract
This paper presents a concept of optimizing the resin transfer moulding (RTM) process by using model modules which are interacting with in-mould sensors and process control. The basic models for the major sub-domains of the RTM process will be shown and the sensors which need to be considered to provide data for them will be mentioned. The fundamental basics for setting up model blocks will be discussed and the interaction between the sub-domains of the RTM process will be pointed out. Starting points for the optimization procedure of the RTM process will be mentioned.

1. Introduction

The RTM process is used to produce high performance components for the (aero-) space, automotive and naval industry. Most of these parts are mainly applied due to their excellent strength to weight ratio which leads to superior lightweight design features [1].
Figure 1 shows the RTM process-cycle which consists of a cutting, preforming and moulding step continued by resin injection, resin curing and demoulding of the final part.

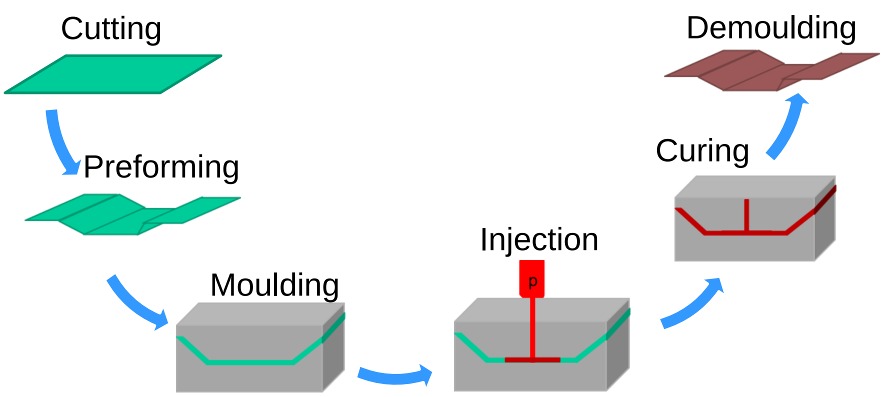

Figure 1. The process-cycle of the RTM process.

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The mechanical properties of the part are set by the constituent materials as well as process parameters, particularly those specifying resin injection and curing. In order to understand the injection and curing step more deeply these steps are broken down on their basic phenomena and described by physical models [2–4].

2. Modular Model Approach for the RTM Process

As shown in Figure 2 the RTM process can be described by four model blocks which all are interacting during the process. Resin flow is only present at the injection step and strongly affected by the rheology of the resin whereas heat transfer and curing are occurring during both, the injection and curing stage. Of course the rheology is also changing during the curing step but due to a steady state of the resin it doesn't affect the process at this time [4–6].

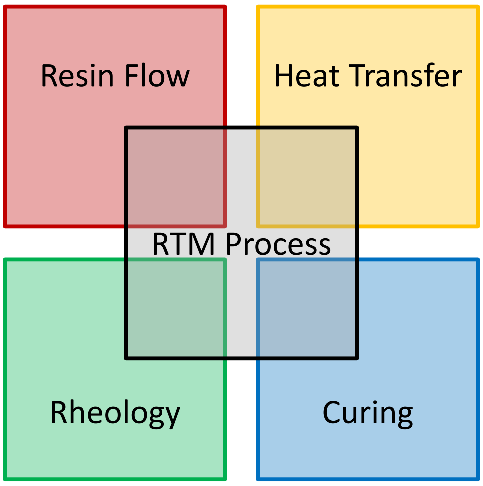

Figure 2. Methodology of interacting model-blocks describing the RTM process.

2.1. Mathematical Models of the Driving Mechanisms

A well-researched topic today is the resin flow [7–10]. Different approaches are used which are describing the flow phenomena in different scales [11] or which are taking different additional phenomena into account [12–14]. Most often it is described by Darcy's law which is stated in Equation (1) where v represents the flow velocity of the resin, η the dynamic viscosity of the resin, K the permeability of the preform and ∇p the preassure gradient in the resin [15].

$$v = -\frac{1}{\eta} K \nabla p. \tag{1}$$

The rheology of a resin depends on three different things: the resin formulation, temperature and curing degree. A few models exist, which describe the dependency of resin viscosity on temperature and curing [4,16–18]. For fast curing reactions the gel model is often used and appears to be the most accurate [4]. It is stated in Equation (2).

$$\eta = \eta_0 e^{\left(\frac{E_\eta}{RT}\right)} \left(\frac{\tau_{gel}}{\tau_{gel}-\tau}\right)^{f(\tau,T)}. \tag{2}$$

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In this case η_0 is the zero–time viscosity, E_η is the activation energy for viscosity, R is the universal gas constant, T is the absolute temperature, τ_{gel} is the conversion of resin reaction groups (for instance epoxide) at the gel point and τ is the actual conversation of resin reaction groups.
The function f is most often defined by the two constants A and B as stated in Equation (3). It also may contain the temperature T to represent the temperature dependency more deeply.

$$f = A + B\tau. \tag{3}$$

For the heat transfer two different states have to be taken into account: The state where the resin is flowing through the preform on the one hand and the state where the mould is completely filled and no resin movement can be observed on the other hand. During the injection step the diffusion term in the heat transfer equation cannot be neglected leading to Equation (4) [4,10,19]. It has been shown for RTM processes that resin and fibers are in thermal equilibrium after a short time [20].

$$\rho C_p \frac{\partial T}{\partial t} + \rho_r C_{pr}(v_r \nabla T) = \nabla(\lambda \nabla T) + \phi \Delta H G. \tag{4}$$

In Equation (4), ρ represents the overall density which can be calculated by a mixing law considering the density of the resin and the fibers. C_p represents the specific heat, also calculated by a mixing law, $\partial T/\partial t$ denotes the change of the temperature over time. ρ_r is defined as the density of the resin and C_{pr} is the specific heat of the resin. v_r represents the resin velocity during the injection phase and gets zero during the curing step. On the right hand side of the equation, λ represents the effective thermal conductivity which also can be calculated by a mixing law. The porosity of the material is defined as ϕ, ΔH represents the reaction heat and G stands for the reaction rate [4].

In order to mathematically describe resin curing, a variety of models are existing [14,21,22]. Most of them are specific for certain types of resin due to their different curing behavior [16,23,24]. Therefore, it makes sense to work with different curing modules which can specialize themselves on the used resin. For the present concept, a model which is able to describe epoxy resin curing is chosen. The model which is shown in Equation (5) is known as an Arrhenius-type model [25]:

$$\frac{d\alpha}{dt} = A_c e^{\left(-\frac{E_a}{RT}\right)} \alpha^m (1-\alpha)^n. \tag{5}$$

Here, $d\alpha/dt$ stands for the reaction rate, A_c is an empirically determined Arrhenius constant, E_a stands for the activation energy while R is the universal gas constant, α is the curing degree and m and n are reaction orders.

2.2. Model Parameterization

To earn profit out of the presented models and achieve an optimization purpose there has to be a data input to the models. Two different parameter classes could be found in the models presented above: Parameters which can be measured during the process and parameters which need to be measured before. Considering Equation (1) this means that the viscosity η of the resin and the permeability K of the preform need to be found out before the process while the flow velocity v and the pressure gradient ∇p can only be measured during the process. To produced measurement data within the running RTM process sensors [26] need to be integrated into the injection unit as well as into the mould. Figure 3 shows the basic concept of the data generation process. $\dot{V}$ stands for the volume flow of the resin which is injected into the mould during the injection step and x describes the position of the sensor. The resin flow front can be derived from the sensor signals.

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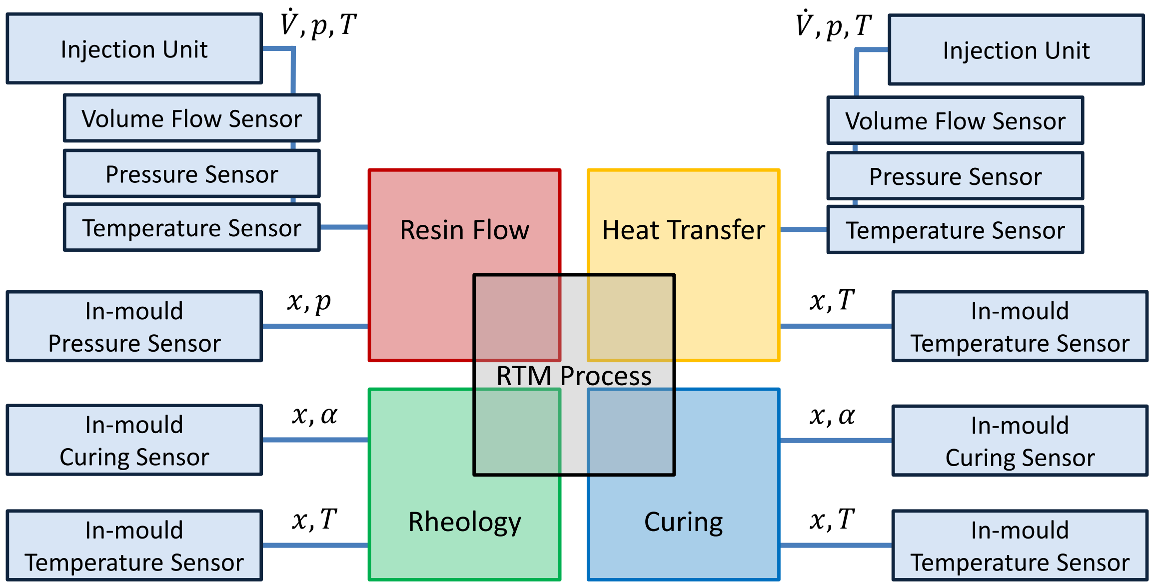

Figure 3. Concept of sensors providing data to the model modules.

As one can see in Figure 3 most of the data needed for the models can be provided by a limited number of sensors. This is due to strongly linked phenomena in the RTM process. For instance the curing affects the rheology of the resin which has a big impact on the resin flow.

The aim is to get an optimized process monitored by the sensors and automatically controlled by a central control unit. Optimization parameters will be (a) minimal void content, (b) shortest cycle time and (c) optimal mechanical performance of the final part. In order to achieve this optimization, models need to be found which are able to generate pressure and temperature curves which can be followed by the injection unit and the heat treatment of the resin and mould.

2.3. Optimized Mould Filling

The principle of operation of the model-based composite processing concept is explained here with the example of optimized mould filling. As Matuzaki et al. have shown in their studies, there is an ideal resin flow front velocity which leads to minimal void content in the final part [27]. The central control unit of the process provides a pre-specified pressure curve for the injection unit which should provide this flow front velocity. While injecting the resin, the control unit observes the flow front and determined whether parameters of the pressure curve need to be adapted. By comparing the arrival time of the resin flow front at the sensors positions with the predicted arrival time, differences can be automatically detected. If there is a time difference, the pressure curve will be changed such that the predicted and measured arrival time fit together.

A second part of process optimization will be the reduction of the cycle time. This can mainly be achieved by reducing the curing time of the resin. In a first step the resin will be characterized by means of differential scanning calorimetry (DSC). This provides data for parameterizing the curing model. Then, the curing degree will be tracked over time by an in-mould mounted sensor. Referring to the optimized curing curve from the model the central control unit will provide an optimized heating cycle for the mould to reduce curing time.

Preceded measurements of the resin viscosity over temperature will be taken into account to achieve minimal flow resistance. Furthermore the rheology data will be used to predict the resin flow front advancement.

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3. Conclusion

This work presents the basics for setting up a model-based optimized RTM process. By using a modular concept it is possible to fit the different models directly to the needs of the used materials. In order to understand the background of the RTM process more deeply models covering the four major phenomena were presented. It was shown which sensors must be integrated into the mould to generate data which is needed for the models. The presented optimization method points to minimize void content in the final part and shorten the cycle time by reducing the time for the curing step.
The further steps in this study include building up a testing mould which is capable of handling the sensors for online measurements. A design of experiments study will be carried out to proof the concept and provide data for further research.

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References

[1] J. A. Holmberg, and L. A. Berglund. Manufacturing and performance of RTM U-beams. *Composites Part A: Applied Science and Manufacturing*, 28: 513–521, 1997.
[2] B. J. Henz, K. K. Tamma, R. Kanapady, N. D. Ngo, and P. W. Chung. Process modeling of composites by resin transfer molding: practical applications of sensitivity analysis for isothermal considerations. *International Journal of Numerical Methods for Heat & Fluid Flow*, 13: 415–447, 2003.
[3] M. Deléglise, P. Le Grognec, C. Binetruy, P. Krawczak, and B. Claude. Modeling of high speed RTM injection with highly reactive resin with on-line mixing. *Composites Part A: Applied Science and Manufacturing*, 42: 1390–1397, 2011.
[4] A. Shojaei, S. R. Ghaffarian, and S. M. H. Karimian. Modeling and simulation approaches in the resin transfer molding process: A review. *Polymer Composites*, 24: 525–544, 2003.
[5] A. Shojaei, S. R. Ghaffarian, and S. M. H. Karimian. Simulation of the three-dimensional non-isothermal mold filling process in resin transfer molding. *Composites Science and Technology*, 63: 1931–1948, 2003.
[6] A. Shojaei, S. Reza Ghaffarian, and S. M. H. Karimian. Three-dimensional process cycle simulation of composite parts manufactured by resin transfer molding. *Composite Structures*, 65: 381–390, 2004.
[7] D. S. Cairns, and S. M. Rossel. *Fluid flow modeling of resin transfer molding for composite material wind turbine blade structures*. Sandia National Laboratories, 2004.
[8] R. Chen, C. Dong, Z. Liang, C. Zhang, and B. Wang. Flow modeling and simulation for vacuum assisted resin transfer molding process with the equivalent permeability method. *Polymer Composites*, 25: 146–164, 2004.
[9] K. M. Pillai. Modeling the Unsaturated Flow in Liquid Composite Molding Processes: A Review and Some Thoughts. *Journal of Composite Materials*, 38: 2097–2118, 2004.

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[10] A. Saad, A. Echchelh, M. Hattabi, and M. E. Ganaoui. A fast computational model to the simulation of non-isothermal mold filling process in resin transfer molding. *Polymer Composites,* 32: 857–868, 2011.
[11] C. Lekakou, and M. G. Bader. Mathematical modelling of macro- and micro-infiltration in resin transfer moulding (RTM). *Composites Part A*, 29A: 29–37, 1998.
[12] H. Tan, and K. M. Pillai. Multiscale modeling of unsaturated flow in dual-scale fiber preforms of liquid composite molding I: Isothermal flows. *Composites Part A: Applied Science and Manufacturing*, 43: 1–13, 2012.
[13] H. Tan, and K. M. Pillai. Multiscale modeling of unsaturated flow of dual-scale fiber preform in liquid composite molding II: Non-isothermal flows. *Composites Part A: Applied Science and Manufacturing*, 43: 14–28, 2012.
[14] H. Tan, and K. M. Pillai. Multiscale modeling of unsaturated flow in dual-scale fiber preforms of liquid composite molding III: reactive flows. *Composites Part A: Applied Science and Manufacturing*, 43: 29–44, 2012.
[15] H. Darcy. *Les Fontaines publiques de la ville de Dijon*. Victor Dalmont, 1856.
[16] A. Shojaei, H. Farrahinia, and S. M. R. Pishvaie. Effect of system of initiators on the process cycle of nonisothermal resin transfer molding – Numerical investigation. *Special Issue: Flow Processes in Composite Materials*, 41: 138–145, 2010.
[17] N. Kiuna, C. J. Lawrence, Q. P. V. Fontana, P. D. Lee, T. Selerland, and P. D. M. Spelt. A model for resin viscosity during cure in the resin transfer moulding process. *Composites Part A: Applied Science and Manufacturing*, 33: 1497–1503, 2002.
[18] M. Naffakh, M. Dumon, and J.-F. Gérard. Modeling the chemorheological behavior of epoxy/liquid aromatic diamine for resin transfer molding applications. *Journal of Applied Polymer Science*, 102: 4228–4237, 2006.
[19] C. L. Tucker III, and R. B. Dessenberger. Governing Equations in Flow and Heat Transfer in Stationary Fiber Beds. *Flow and Rheology in Polymer Composite Manufacturing*: 257–323, Elsevier Science, 1994.
[20] S. G. Advani. *Flow and rheology in polymer composites manufacturing*. Elesvier, 1994.
[21] T. S. Mesogitis, A. A. Skordos, and A. C. Long. Stochastic simulation of the influence of cure kinetics uncertainty on composites cure. *Composites Science and Technology*, 110: 145–151, 2015.
[22] R. D. Sudduth. Simplified Modeling of the Dynamic Gel Time and/or the Dynamic Gel Temperature for a Thermosetting Resin or Composite. *Journal of Composite Materials*, 37: 985–1009, 2003.
[23] D. Roşu, C. Caşcaval, F. Mustaă, and C. Ciobanu. Cure kinetics of epoxy resins studied by non-isothermal DSC data. *Thermochimica Acta*, 383: 119–127, 2002.
[24] Y. Nawab, X. Tardif, N. Boyard, V. Sobotka, P. Casari, and F. Jacquemin. Determination and modelling of the cure shrinkage of epoxy vinylester resin and associated composites by considering thermal gradients. *Composites Science and Technology*, 73: 81–87, 2012.
[25] Z. Liu, J. Xiao, S. Bai, and W. Zhang. Study on phenomenological curing model of epoxy resin for prediction of degree of cure. *Journal of thermal analysis and calorimetry*, 109: 1555–1561, 2012.
[26] S. Konstantopoulos, E. Fauster, and R. Schledjewski. Monitoring the production of FRP composites: A review of in-line sensing methods. *Express Polymer Letters*, 8: 823–840, 2014.
[27] R. Matuzaki, D. Seto, M. Naito, A. Todoroki, and Y. Mizutani. Analytical prediction of void formation in geometrically anisotropic woven fabrics during resin transfer molding. *Composites Science and Technology*, 107: 154–161, 2015.

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