A MODULAR MODEL-BASED PROCESSING CONCEPT FOR AN OPTIMIZED PULTRUSION PROCESS MANAGEMENT

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Abstract
Pultrusion represents an industrially well-established process for the continuous fabrication of fibre-reinforced polymer composite profiles. The existing scientific literature focuses on the analysis of singular phenomenological aspects occurring inside the pultrusion die. The present paper introduces the concept of a modular model-based process control system. The basic idea of the concept is to combine material properties, processing parameters and the process control strategy into a superior processing model. A first basic version of a processing model for the pultrusion of composite profiles with thermosetting matrix materials is presented. It incorporates a curing kinetics model in terms of an Arrhenius-type differential equation for the curing rate as a function of curing time and temperature.

1. Introduction
The continuous fabrication of fibre-reinforced composite profiles based on polymer matrix materials has started in the 1960's with the introduction of the pultrusion process [1]. The fundamental process flow is simple: fibre rovings are impregnated and subsequently drawn through a heated pultrusion die, where the curing (thermoset matrix materials) takes place in order to obtain a fully solidified composite profile [2]. Figure 1 shows a scheme of the governing components in a pultrusion line.

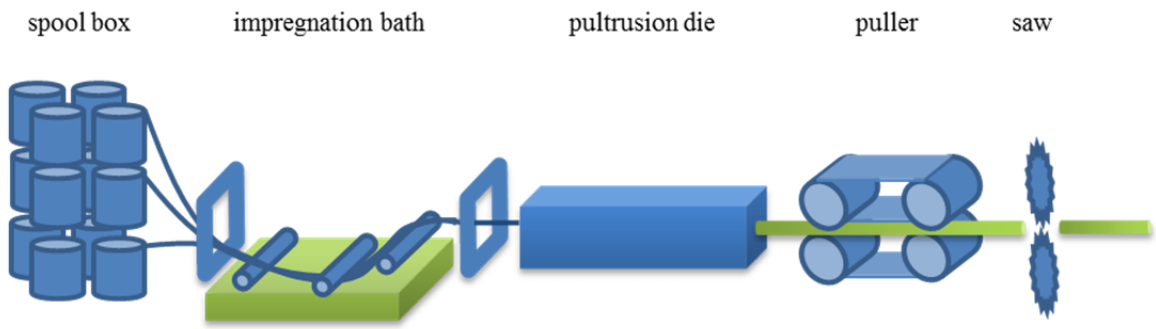

Figure 1: Scheme of a pultrusion line with the governing components.

Compared to other techniques for processing of polymer-based fibre-reinforced composites, this method shows a very simple setup and permits the efficient and economic fabrication of mechanically powerful profiles [1; 3].

However, the scientific interest in this processing method is surprisingly sparse and is mainly concentrated on approaches for modeling curing kinetics and heat flow. Valliappan et al. [4] developed a model for the prediction of the curing degree as well as the temperature profile in a cylindrical composite profile. Therein, the overall processing speed and the temperature conditions along the inner die wall are identified as the most governing entities with respect to the curing degree. The works presented by Liu et al. [5–7] as well as Joshi and Lam [8] use of finite element analysis for the three-dimensional simulation of pultruded I-beams and irregularly shaped profiles.

The cited papers aim at modeling singular aspects of the pultrusion technique as well as their experimental verification. The combination of singular sub-models and their complex interrelations into a comprehensive numerical model is barely applied so far. First approaches in this area are reported by Wilcox and Wright [9] and [10]. Therein, the authors apply artificial neural networks and genetic algorithms. The application of artificial neural networks is considered to be disadvantageous due to (a) the need for considerable amounts of training data, and (b) the fact, that the knowhow about coherence and interrelation of the individual parameters is hidden inside the required transfer functions and parameter weightings. Thus, the fundamental insight into the process and the governing mechanisms remains inaccessible.

In the article at hand, the concept of a modular processing model is presented that extends the existing approaches by incorporating material properties (e.g. fiber volume content, viscosity, curing behavior) and processing parameters (die temperature, processing speed) as well as the pultrusion line setup (type of impregnation, die geometry, heating setup) and the process control strategy (control of the processing speed, feedback control for the die temperature).

2. Modular Model-Based Control of the Pultrusion Process

2.1. The Basic Idea

The basic idea of a model-based control concept for the pultrusion process is to:

- combine discrete and well-studied phenomenological models of the pultrusion process, e.g. the curing behaviour along the length of the heated die or the heat flow inside the material, with processing parameters and material properties into a superior processing model as shown in Figure 2, and
- incorporate this phenomenological processing model into the control system in order to ensure optimized processing conditions. This requires continuous acquisition and consideration of quality related parameters.

The modular structure of the concept is important as it allows the handling of various facility configurations (e.g. impregnation of the fibre rovings in an open resin bath as well as a closed impregnation box, processing of thermoset as well as thermoplastic matrix materials) on the one hand and the flexible incorporation of phenomenological sub-models on the other hand.

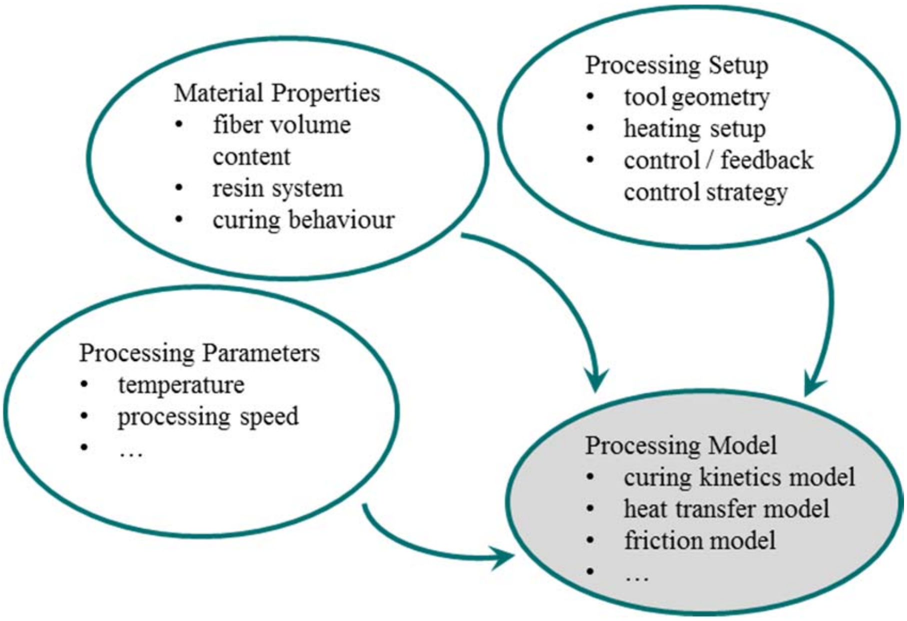

Figure 2: Scheme of the modular processing model with phenomenological sub-models, which are based on material properties as well as the processing setup and processing parameters

2.2. Benefits

The main advantages of the proposed modular model-based process control concept can be summarized as follows:

- gain substantial knowledge about the physical mechanisms driving the pultrusion process,
- ensure constantly high quality of the pultruded profiles by means of an optimized process management,
- continuously acquire quality related parameters, and
- intrinsically provide the basis for comprehensive process monitoring and documentation as well as for a self-regulating process control system.

3. Optimized Pultrusion Process Management

3.1. Process Control Strategy

Before starting to think of implementing a specific process control task, it is important to define the overall aim, i.e. the actual strategy of the control system. Considering the pultrusion process with thermoset matrix materials, a couple of different process control strategies can be specified:

- quality strategy:
  - ensure that the pultruded material attains a certain level of curing degree after passing through the heated die,
  - avoid thermal degradation of the polymer matrix material by limiting the permissible maximum die temperature.
- quantity strategy:
  - optimize the throughput of the pultrusion line, i.e. run the process at maximum processing speed.
- combined strategy:
  - concurrently fulfil quantitative as well as qualitative requirements.

Probably the most important task when running a pultrusion process with thermoset matrix materials is to attain a certain level of curing degree as the pultruded material leaves the heated die, as this is crucial with respect to the mechanical properties of the material. Thus, our first aim is to develop a control strategy to ensure a specific minimum curing degree $\alpha_{\min}$ of the thermoset matrix material in the pultruded composite profile.

3.2. Heating Strategy and Temperature Control

The hardware part of the heating concept chosen for the pultrusion line to be set up in our laboratory is built on a series of heating elements mounted in two U-shaped die holders. The actual pultrusion die is clamped between the two die holder shells. This concept enables the pultrusion die to be flexibly replaced in order to alter the geometry of the composite profile to be manufactured. Figure 3 shows a CAD design of this hardware concept.

Figure 3: CAD design of the pultrusion die with die holder and heating elements.

Along the length of the pultrusion die, the heating elements are coupled pairwise (one being located in the lower and upper die holder, respectively) to form heating zones, where each one is being actuated individually by means of a temperature controller. In order to fulfil the loop control tasks, the temperature controller is supplied by:

1. temperature measurement values extracted from thermocouples mounted inside the heating elements, as well as
2. setpoint values provided by the user over a graphical user interface from a control software running on a PC-platform.

The benefit of applying heating elements instead of heating plates (typically found in industrial pultrusion lines) is that the temperature distribution established along the die length that can be adjusted more flexibly. However, for the calculations described in the following sections, a constant temperature distribution along the pultrusion die is selected.

3.3. Assumptions

For a first basic version of the introduced model-based control concept, the following assumptions are made:

- the temperature is assumed to be constant over the entire surface of the inner die wall, thus neglecting:
  - temperature inhomogeneity due to heat transfer or heat loss from the die towards the die holder and the surrounding area,
- the temperature distribution over the cross section of the pultruded profile is considered to be homogeneous, neglecting effects like:
  - heat flow from the die contact area towards the inner regions of the profile,
  - heat generation as a result of an exothermic reaction between resin and hardener, or
  - heat due to friction forces between the pultruded material and the die wall,
- the only mechanism considered in our first version of the processing model is the curing kinetics.

3.4. Curing Kinetics Model

The resin cure kinetics is modelled by means of a general form that can represent the kinetics for a large number of thermosetting resin systems. Mathematically, the following Arrhenius-type differential equation for the curing rate is applied [11]:

$$\frac{d\alpha}{dt} = (k_1 + k_2\alpha^m)(1-\alpha)^n, \tag{1}$$

with:

$$k_{1,2} = A_{1,2}e^{-\frac{E_{A1,2}}{RT}}. \tag{2}$$

Therein, α denotes the curing degree as a function of processing time t and the absolute temperature $T[K]$. Moreover, A_1 and A_2 indicate non-dimensional pre-exponential factors, E_{A1} and E_{A2} term activation energy values $[J/mol]$ and the non-dimensional parameters m and n specify the reaction order. Finally, R $[J/(K \cdot mol)]$ represents the ideal gas constant.

3.5. Numerical Solution

In order to accomplish the overall aim of the control system as stated in Section 3.1, i.e. ensuring a specific minimum value $\alpha_{\min}$ for the curing degree as the pultruded material leaves the heated die, we need to numerically solve the reaction kinetics model given in Equation (1). Thus, a set of parameters describing the curing behaviour of a specific thermosetting matrix material is needed. As reported by Kamal and Sourour [11] or Theriault et al. [12], differential scanning calorimeter (DSC) measurements are an appropriate means to determine the required values.

For proving our concept, we decided to rely on a set of parameters for a vinyl ester resin system reported by Li et al. [13; 14]. The individual values are listed in Table 1.

$A_1[-]$	$A_2[-]$	$E_{A1}\left[\frac{J}{K \cdot mol}\right]$	$E_{A2}\left[\frac{J}{K \cdot mol}\right]$	$m[-]$	$n[-]$
0.00663	3.14	4721	11643	0.63	2

Table 1: Numerical values for the Arrhenius-type reaction kinetics model.

Based on this set of parameters, a numerical solution algorithm following the classical Runge-Kutta method [15] has been implemented. The nonlinear differential equation describing the curing kinetics model has then been solved with a series of pre-specified temperature values, as shown in Figure 4.

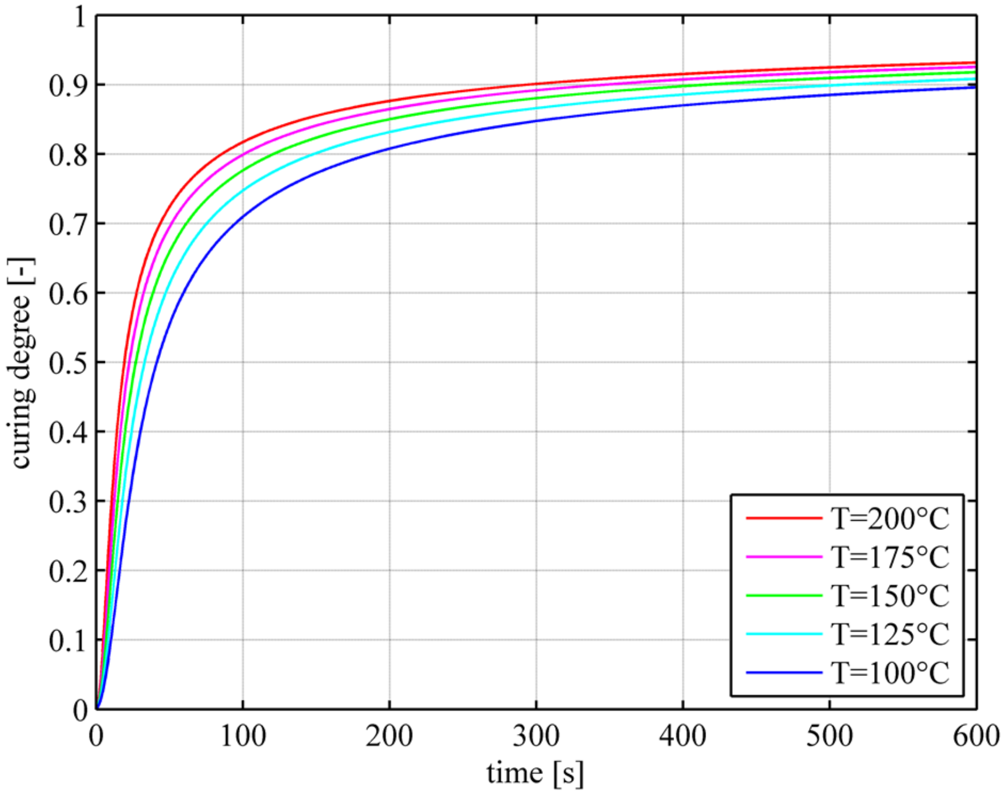

Figure 4: Results of numerically solving the reaction kinetics model for a series of pre-specified temperature values T.

Obviously, higher temperature values lead to a faster curing of the thermosetting matrix material or, in other words, higher temperature values lead to higher values for the final curing degree. For our sample evaluation, the pultrusion speed is chosen to be constant, thus the time that the thermosetting matrix material needs to run through the heated die is given as the quotient of pultrusion speed v and die length l. Here, a time period of 600 seconds has been chosen for the material to run through the die.

The information about the curing characteristics can now be used for actuating the appropriate die temperature in order to attain a certain final curing degree for the pultruded material. The following implementation strategies are available for this task:

1. combined offline/online solution:
    a. offline setup of a look-up-table (LUT), holding the predicted final curing degree values depending on processing speed (i.e. curing time) and curing temperature, and
    b. online readout of the appropriate curing temperature from the LUT based on the processing speed and the minimum curing degree specified by the user.
2. entirely online solution:
    a. implementation of an algorithm for numerically solving the curing kinetics model at runtime of the control software, and
    b. online execution of this solution algorithm as the user chooses or modifies the values for the processing speed or the desired curing degree.

4. Summary and Outlook

The present paper introduces the concept of a modular model-based process control system for an optimized pultrusion process management. The basic idea of the concept is to combine material properties and processing parameters with the pultrusion line setup as well as the process control strategy into a superior processing model, which is then incorporated in the control system with the aim of ensuring optimal process conditions and constantly high product quality.

A first basic version of a processing model for the pultrusion of composite profiles with thermosetting matrix materials is presented. It incorporates a curing kinetics model in terms of an Arrhenius-type differential equation for the curing rate as a function of curing time and temperature. A sample evaluation of this model following the classical Runge-Kutta method is shown based on a set of material parameters reported in the literature.

In the near future, our activities will concentrate on approaches towards the implementation of a numerically robust and efficient algorithm for solving the Arrhenius-type differential equation describing the curing kinetics model. Moreover, the assumption of a constant temperature distribution along the die will be modified towards a more realistic temperature profile in a next step. Thus, a model addressing heat flow as well as heat losses will be incorporated.

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