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"Autonomous control of gap distance and angel of attack in slot-die coating"

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Abstract

Despite the rapid scale-up of battery production which could be observed the last years, various challenges remain in electrode production. In particular, the high scrap rates of up to 40 % during the coating process of the electrodes offer enormous potential in terms of economic and ecological aspects. To counter these problems, a system concept was developed that can react autonomously to process conditions and thus reduce scrap. For this purpose, with the gap distance and the angle of attack deliberately two parameters are varied during slot-die coating, which react quickly and furthermore do not affect the productivity of the system. By adapting the position of the slot-die, it is possible to achieve an optimum operating point in the coating window and thus improve the quality of the results without regulating the volume flow or the web speed. The aim is both to shorten the start-up process by a fast and precise correction of the slot-die position on the basis of the coating result and to increase the quality in the adjusted operation. With the help of the corresponding measuring technology and the control based on the coating result, the processing of slurries with fluctuating fluid properties or the processing of new recipes is simplified and possible without manual intervention. The concept is possible for existing plants as well as for new plants.

Keywords: slot-die coating; autonomous; battery manufacturing; electrode; scrap reduction

1. Introduction

Developments in the field of battery production in recent years have been characterised by rapid progress. Through the efforts of industry and research, the production capacities of cell manufacturers have multiplied within the last years. On the other hand, production processes have been optimised as well as cell chemistry. In addition to established batteries, sodium-ion or solid-state batteries can thereby be mentioned as examples. [1, 2]

The aforementioned rapid further developments require manufacturers to react accordingly to changing boundary conditions. According to the current state of the art, existing plants cannot do this and are optimised for one operating point and one material system. A changeover is avoided as far as possible in order to avoid problems and high scrap rates.

Even in stable operation, manufacturers accept scrap rates of up to 40%. [3] This is critical from both an economic and an ecological point of view.

Considering the manufacturing costs of a Li-ion battery, they are largely made up of material costs, which account for 74.9% of the costs of cell production. [4] This makes the optimisation of material-intensive processes, especially the coating process, of particular interest. This paper therefore focuses on the coating process. It should also be noted, that due to the continuous roll-to-roll processes, the coating rejects must also pass through the downstream processes. As this is associated with high energy costs, especially in the case of drying and

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vacuum drying, it emphasizes the importance of low scrap rates. [4] In general, the coating quality as input for the downstream processes is also the needed basis for high-quality cells.

1.1 Slot-die coating as state of the art

For the coating of battery electrodes, slot-die coating is used as the current state of the art. It is characterised both by high productivity with a coating record of up to 150 m/min [5] and industrially common systems with coating widths of about 1000 mm to 1500 mm and by a precise coating result. The active material, the so-called slurry, is applied to the substrate, which is usually made of aluminium or copper. The substrate is moved at a constant speed under the slot-die.

1.2 *Characteristic process parameters*

The slot-die coating process can be described by the parameters shown schematically in Figure 1. The slurry is pumped at a constant flow rate (q) into the slot-die, which has an opening gap (S). The slot-die is located at a distance (G) from the substrate. The latter moves with a constant velocity (u) below the slot-die. The theoretical wet film height (h*) results from the volume flow, outlet width and web speed. Looking at the cross-section of the coating, it can be observed that an excess height is formed in the edge areas. This can be characterised by the width (b_{edge}) and the height (h_{edge}) of the respective sides. The areas extend until the constant wet film height (h) is reached in the interior of the coating.

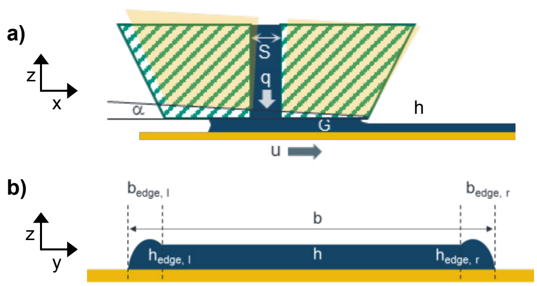

Figure 1: a) Slot-die with relevant parameters b) cross section of the resulting wet film with edge elevation

Parameters for slot-die coating

S	gap between the lips of the slot-die
q	volume flow of the slurry
u	speed of the substrate
G	**Gap between slot-die and substrate**
α	**angle of the slot-die regarding the substrate**
h*	theoretical wet film thickness
h	wet film thickness
h_{edge}	highest wet film thickness in the area of the edges
b	width of the wet film
b_{edge}	width of the wet film until reaching the constant height

1.3 Suitability of different parameters for inline control

According to our own research, there are currently no systems available with inline control for optimising the coating result. Instead, the focus is on maintaining initially set parameters after achieving satisfactory results. Considering the high scrap rates, the potential for improvement is high. For the coating process, the introduced parameters q, u, G and α can be used to influence the coating result. Since the volume flow and the web speed have a direct influence on the productivity of the system and also exhibit inertial behaviour, this paper concentrates on the variable gap distance and angle of attack. It was already shown by the Thin Film Technology (TFT) at KIT, that these parameters have a direct impact on the quality of the coating result, especially the wet film thickness and the edge elevation. [6] This has a direct influence on the amount of scrap as well as the quality of the process. Since volume flow rate and web speed are not considered as control parameters, the focus of the setup described is on achieving good coating results for a given set of machine settings.
The coating quality in this context is defined as the dimensional accuracy of the wet film profile. In particular the three values - maximum edge elevation, average wet film height and width of the edge areas until the average wet film height is reached – are considered. The integral of the wet film profile over the coating width is given by the constant volume flow and the web speed, which means that these variables are directly related to each other.

2. Concept and implementation of actuating variables

As derived in section 1, the parameters gap distance and angle of attack were identified as suitable manipulable variables for the coating process. The motorized adjustment option is a necessary prerequisite for the control of the process. For this purpose, a concept for the integration of the motorized adjustment options was developed, which will be presented in the following including a weight compensation and the avoidance of alternating loads.

2.1. Setup

The used setup consists of a Development Coater © from TSE Troller AG, consisting of a support on which the slot-die is attached and a high-precision roller on which the coating is applied. This is a test system, which can be used to perform coating tests with reduced cost and system effort by eliminating the need for substrate and subsequent drying processes. The structure is shown schematically in Figure 2.

2.2. Axis position and requirements

For the variation of the identified parameters gap distance (G) and the angle of attack (α), two axis are added to the setup. For G a threaded rod is used as the first movement axis in order to move the entire nozzle support towards the precision roller. Furthermore, the inner slot-die support (yellow assembly in Figure 2) can be raised or lowered via a gear wheel at the flank facing away from the roll. This rotates the support and the slot-die around the axis marked in red. When arranging the axes of movement, it should be noted that the axis of rotation is located at the tip of the slot-die, as shown in Figure 1. Thus, a decoupled setting of the two manipulated variables is possible. This is of great importance due to the interaction of the two parameters with regard to the coating result. Based on the preliminary work [7], a minimum necessary increment of 15 µm for the adjustment option was defined for the gap distance and 0.2° for the angle of attack. To define this precision target, a wet film height and width variation of less than 1.5% was used as the quality target to be achieved.

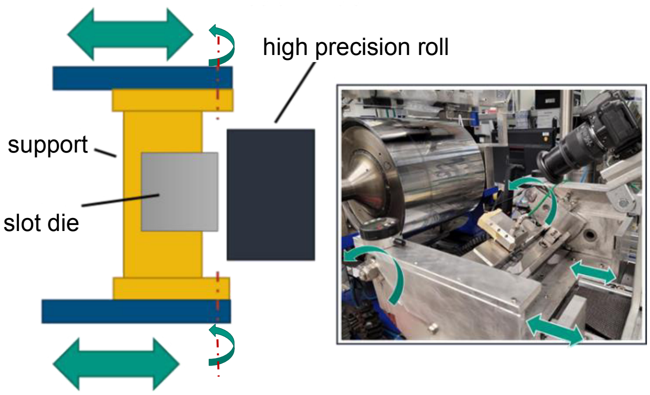

Figure 2: Schematic representation of the coating setup with the direction of movement of G and α (green) and the axis of rotation for the nozzle support (red), KIT-TFT Lab, Development Coater© (TSE)

2.3. Implementation and components

Closed-loop stepper motors are used for the implementation, which are ideal due to the compact installation space and the high passive holding torque. In addition, the loss of the absolute position can be avoided due to the integrated encoder. A correspondingly fine increment can be achieved in combination with high-precision planetary gears. The structure results in a theoretical increment corresponding to 1.4 µm gap distance or 0.03° of the angle of attack in full step mode. This finer resolution allows the previously defined target values to be checked.

2.4. Design features

Two aspects should be emphasized in the implementation. First, the weight of the nozzle support to be rotated is compensated by an adaptive spring element. Depending on the slot-die used, the force to be compensated can vary, which is why this setting is necessary when changing the slot-die. The aim of this measure is to reduce the required maximum torque of the drive in order to be able to make it smaller. In addition, the spring element can be adjusted so that the holding torque of the de-energized stepper motor of 6 Nm after the gear stage is sufficient to hold the position. This allows energy-saving operation and protects the motor.

On the other hand, it is important, that alternating loads are avoided, as this has a negative effect on the precision achieved. Therefore, a preload of the respective axes is sought. When setting the angle of attack, this is achieved by the weight of the nozzle support and slot-die. This makes precise adjustment of the spring element necessary. To adjust the gap distance, the support is pneumatically pressed in the direction of the roller.

2.5. Integration in holistic test setup

The structure is supplemented by appropriate measurement technology, as shown in Figure 3. For this, a confocal sensor is used to detect the gap distance. This sensor was chosen due to its better transferability to different system concepts and material independence. The coating quality is recorded according to [7] using the wet film profile, measured by a 2D triangulation sensor, and optical defect detection using a line scan camera.

Figure 3: Setup with components – (1) High precision roll; (2) slot-die; (3) doctor blade; (4) gap sensor; (5) 2D-triangulation sensor; (6) line scan camera

2.6. Impact of control variables on the coating result

A major advantage of the new design is the possibility of continuous precise adjustment of the angle of attack and gap distance during operation. In order to verify this and compare it with previous observations, a continuous parameter variation was performed over the parameter space considered with a constant rate of change. Figure 4 shows an example of the wet film profile in the edge region as a result of a constant variation of the angle of attack from +2° (divergent gap) to -2° (convergent gap). The continuous manipulation of the parameters and the uninterrupted observation of the edge profile should be emphasized, which in combination provide valuable insights into the behavior of the system.

The continuous adjustment of the parameters makes it possible to measure the effects and interactions of setting parameters directly in a test run. In the course of the wet film profile, which can be seen in Figure 4, a trend from high edge protrusions as well as defects at positive angles of attack to reduced edge protrusions at negative angles of attack is clearly visible.

Thus, the correlations shown in [6] could be repeated and the functionality of the system for inline parameter adaptation could be verified.

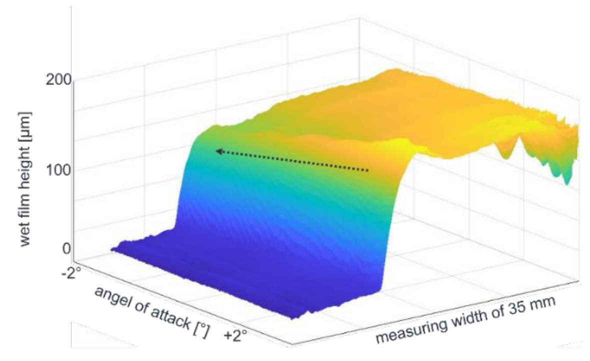

Figure 4: Time course of the wet film profile with continuous variation of the angle of attack from +2 ° to -2 ° with a visible trend in the edge elevation

3. Control concept

The mechanical implementation of the setting options for gap distance and angle of attack, as described in section 2, allows motor-supported variation of the manipulated variables during the coating process. A fuzzy controller is used to identify new target values for the parameters, which derives the necessary corrective measures on the basis of the integrated measurement technology (see section 2.5). The intended concept, which is currently being implemented, is presented in this section.

3.1. Advantages of fuzzy-control for slot-die coating

A fuzzy controller can be divided into three steps as shown schematically in Figure 5. This is the fuzzification of the control variables followed by the rule-based decision making. Finally, the result is defuzzified again and translated into concrete control variables. This offers the possibility to implement the rules for decision making independently from the produced electrode as well as from the concrete plant. Instead, the rules are based on qualitative relationships between the quality characteristics and the manipulated variables. Most of them are already available as operator knowledge or can be identified with the new setup and a continuous inline variation, as shown in Figure 2.

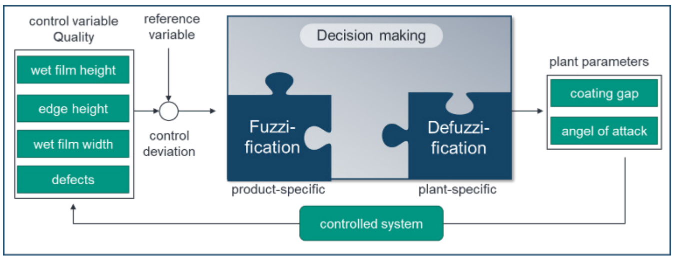

Figure 5: Controller Concept with product-specific fuzzification and plant-specific defuzzification

This means that the controller can be implemented independently of the product and the plant, which allows good transferability and does not require specific models of the processed material or the plant behavior.

3.2. Implementation of the fuzzy-control

During fuzzification, the measured variables are translated into linguistic terms. This module is implemented depending on the specified product parameters and tolerances. For this purpose, a percentage division of the tolerance window can be made in a standardized way. In the simplest case, this results in a membership function with "good" in the tolerance range as well as "too low" and "too high" which reach into the tolerance range, as shown schematically in Figure 6.
For the defuzzification, the results of the decision making are translated into plant parameters. Since it is only here that the linguistic terms are translated into concrete parameters such as motor angles corresponding to the resulting angle of attack and coating gap, only this module needs to be adapted when the controller is applied to another plant.

Figure 6: Schematic membership function

4. Conclusion and outlook

The concept that was developed enables online adjustment of the gap distance and angle of attack parameters. It has already been proven in preliminary work that these variables are suitable for influencing the quality of the coating result. The axes used enable the parameters to be set with repeat accuracy and precision. Thanks to the closed-loop stepper motors, easy integration into various systems can also be expected. In further steps, the previously identified requirements for the increment of the parameters gap distance and angle of attack must be checked. In the event that these sizes are confirmed, the gear stage can be dispensed with, which would have a positive effect on both installation space and costs. For a further assessment, the system is to be used in operation in combination with an online control in order to test how the requirements differ with continuous adaption of the manipulated variables towards an approach of initial set absolute values. Finally a concept for the implementation on different plants is to be developed, to make a fast deployment in existing plants possible.

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