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Implementation of a Fuzzy Controller for Battery Electrode Coating with a Slot Die

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Abstract

Growing awareness of the impact of climate change is accelerating the development of sustainable technologies. One example is the increasing electrification of various systems, such as transport. Lithium-ion batteries are currently the preferred solution for providing the required energy. As a result, the production capacity for these energy storage systems has grown tremendously. Due to this rapid scale-up, low to mid-double-digit percentages of production scrap are common for lithium-ion battery production lines, especially during ramp-up. Nevertheless, process control is largely abandoned. To exploit this enormous potential to reduce costly material scrap, a controller concept for the coating gap and angle of attack in the slot die coating process of electrodes is presented. Extensive expert knowledge is available for this process, describing the fundamental interactions between process parameters and quality characteristics. However, it has not yet been possible to formulate a comprehensive model that predicts this with the required accuracy and is transferable between systems and electrochemical formulations. The data sets required for ML are also only available to a limited extent or are not available for new formulations and systems. Therefore, there is great potential in the implementation of a fuzzy controller. This paper shows the advantages of a fuzzy controller and the concept's theoretical plant and product transferability. Finally, an exemplary implementation with formulated rules is shown.

Keywords: slot die coating, fuzzy controller, scrap reduction, resilient manufacturing systems

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1. Introduction and Basics

In addition to uncertainties and regularly changing forecasts, the market for battery cells has been characterized by rapid technological development in recent years. This has been made possible by the enormous efforts of industry and research. European production capacities have multiplied, and processes and cell chemistry have been optimized. Further, new technologies, such as sodium-ion and solid-state batteries, are already on the horizon. [1], [2]

The mentioned rapid developments require manufacturers to react quickly to changing boundary conditions. Existing systems cannot achieve this and are optimized for high output at the cost of flexibility and therefore only for one operating point and one material system. To avoid problems and high scrap rates, changeover is avoided as much as possible.

Even in stable operation, a yield of less than 90 % is expected, whereas, for the ramp-up process or changeover, only a 50 to 70 % yield is expected [3]. These high scrap rates are critical from an economic and environmental perspective due to the high material consumption - especially since material costs account for approximately 75 % of cell production costs [4].

The optimization of material-intensive processes, especially the coating process, is of particular interest. This paper therefore focuses on the slot die coating process. It should be noted that due to the continuous roll-to-roll process, localized coating scrap must also pass through the downstream

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processes. The ability to discharge parts of a coil from the process is limited. As the further processing of scrap is associated with high energy costs, particularly in the case of drying and vacuum drying, this underlines the importance of low scrap rates. [4]. The coating process provides the basis for the subsequent process steps and the final cell quality due to the interlinking of the cell production.

1.1 State-of-the-art Electrode Coating

For the coating of battery electrodes, slot die coating represents the state of the art. This process is characterized by high precision and high productivity in continuous operation. In laboratory setup speeds of 150 m/min have already been achieved [5]. Typical coating widths in the industrial environment are in the range of 1000 to 1500 mm. Adjustments to the process are characterized by an iterative and manual approach that relies heavily on the individual expertise of the system operator. Automation therefore offers great potential. One trend in battery cell production is the flexible production as an addition to the currently common plants, optimised for high output at low cost with no variation [6], [7]. Specifically for the coating process, this can be achieved with small improvements to the coating equipment and depends largely on a control loop that can handle the change in material or target properties [8].

The slot die coating process is shown schematically in Figure 1. The process parameters are the volume flow (q) at which the slurry is pumped through the slot die, the web speed of the substrate (u), the gap distance (G) between the substrate and the slot die, as well as the angle of attack (α) between the substrate and the slot die. The wet film profile can be described by the coating width (b), the wet film height (h), and the edge elevation (j). The optimum profile for further processing would be a rectangular shape without any edge elevations. As this is not possible due to the surface tension of the slurry, the aim is to reduce the edges.

1.2 Suitability of Different Parameters for Inline Control

The introduced process parameters q, u, G and α are available to influence the coating process. In addition to the ability to correct the quality characteristics, the reaction and positioning speed is also important for inline control. Since the adjustment of the volume flow and the web speed are system-inherently inertial and have a direct effect on the throughput of the system, they are not considered as target-oriented control variables for a control system. The suitability of the mechanical control variables G and α for correcting the coating quality has already been proven [9]. Optimizing the geometry of the shims [10] or the geometry of the slot die [11], [12] also gives promising result. However, this requires constant adjustment of the nozzle, so this step for in-line control is not being pursued further for the time being.

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.

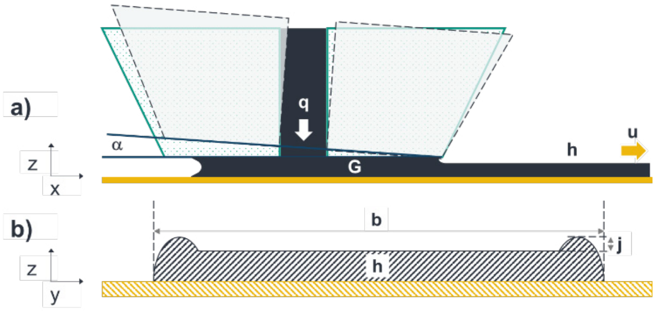

Figure 1: a) Slot die with relevant parameters b) cross section of the resulting wet film with edge elevation

Parameters for slot die coating

q	volume flow of the slurry
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
j	elevation in the edge area
b	width of the wet film
u	web speed

1.4. Test Setup in Laboratory Scale

The laboratory-scale equipment used (development coater from TSE Troller AG) as shown schematically in Figure 2 is used for the isolated observation of the coating step. The electrode slurry is applied to a chrome-plated high-precision roller (1) by means of a slot die (2). This allows the process to be observed without the influence of the substrate and in a material-saving manner. The coating quality is then measured using line laser triangulation sensors (Keyence, LJ-X8060) (3) and a line scan camera (Keyence, CA-HL08MX) (4). Finally, the material is removed from the roller in a slurry trap by a doctor blade (5). The system allows the adjustment of the gap distance and the angle of attack, which has been supplemented by a motorized adjustment through in-house integration [8]. Due to the local offset between the slot die exit and the sensor system, there is a delay of approximately 300 mm between the parameter change at the slot die and the quality measurement. Depending on a supposed process speed of 5 – 60 m / min, this corresponds to approximately 3.5 – 0.3 s.

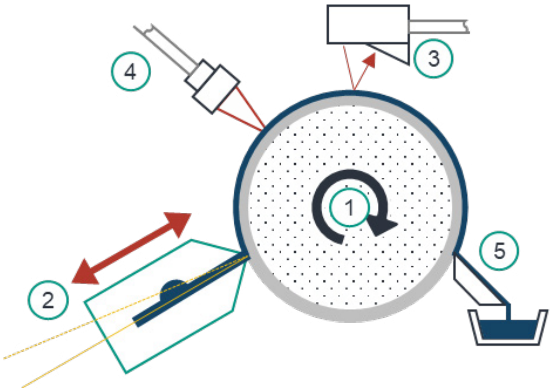

Figure 2: Setup with components – (1) High precision roller; (2) adjustable slot die; (3) 2D-triangulation sensor; (4) line scan camera; (5)

2. Approaches for Controlling the Coating Process

2.1. Requirements for the Control

The goal of the control system is to optimize the coating process for battery electrodes and to achieve reproducible and high-quality results without manual intervention. The following requirements for the controller can be derived from the existing boundary conditions and aims:

- Quality optimization of the wet film in a stable coating
- Maintenance of the stable coating case
- Transferability to other material systems
- Applicability to different coating machinery
- Realization without mathematical models (qualitative expert knowledge available)
- Iterative correction (due to dead time between actuator and measuring element)
- Runtime of < 0.1s (equals one third of the dead time of the system at a speed of 60 m/min)

Transferability to different materials and systems is seen as a prerequisite for achieving meaningful dissemination. The aim is therefore to transfer the created logic with little effort. The quality requirements in the form of tolerances are specified by the product to be manufactured and are therefore individual for each electrode. It is important to be able to specify both the target values and the limits above which a correction should be made.

2.2. Controller Selection

Several options were considered to implement the defined requirements. In principle, a conversion is possible with a large number of controller types. However, the effort and especially the fulfillment of the requirements vary.

Based on the set requirements, a fuzzy controller is identified as appropriate. The transferability of the control approach is seen as particularly promising for the fuzzy controller. The initial situation with available expert knowledge and qualitatively known correlations can also be implemented with this controller with little effort. This means that no physical modeling of the coating process and no extensive data set are required.

2.3. Controller Concept

The key to the implemented architecture is the separation of product-specific, controller logic, and system-specific aspects. This ensures easy transferability of product or system aspects without changing the controller logic. The product-specific variables include the target values and the tolerance ranges of the quality characteristics. These are integrated into the controller by means of fuzzification. The control basis also represents qualitative statements that are assumed to be generally valid in the stable coating state. De-fuzzification is used to translate the controller's decision into system-specific manipulated variables (drive comand for the actuatot motor). This means that only the corresponding component can be adapted during a transfer, which minimizes the effort. The schematic imlementation of the fuzzy control is shown in Figure 3.

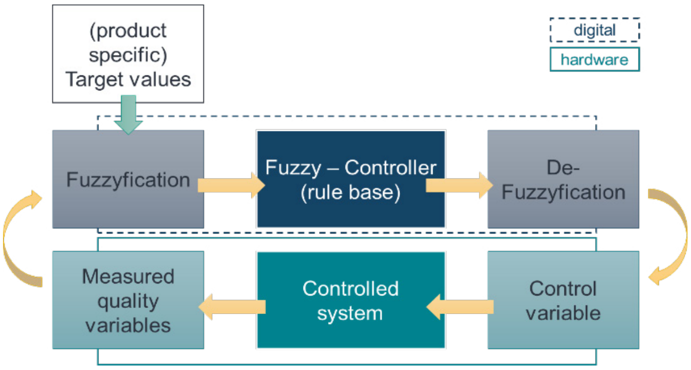

Figure 3: Schematic integration of the fuzzy control in the test setup for electrode coating.

3. Controller Development

The fuzzy controller for the coating step is designed in a Phyton environment. Various libraries can be used here and it is generally regarded as a programming language with a low barrier to entry. This should ensure easy distribution. Since the data from the sensors integrated in the experimental setup are also processed on a computer in Python, an easy integration is expected here. Python version 3.11 is used.

3.1. Expert Knowledge and Qualitative Decision Rules

For the coating step, the three measured variables wet film height, edge elevation and coating width are considered as shown in chapter 1.2. These are to be corrected by means of the gap distance and the angle of attack. Due to the three control variables with only two manipulated variables, not all deviations can be compensated for some cases. An adequate volume flow and coating speed for the required properties is therefore assumed. The control is therefore primarily aimed at optimizing the quality of a stable coating. A stable coating can be expected within the boundaries of the coating window [13], [14].

Essential for the development of a fuzzy controller is an existing base of expert knowledge that qualitatively reflects the relationships and contains the qualitative response to be derived from the process information. In addition to technical books on the fundamentals of the coating process [15], [16], a wide range of current publications on the specific topic of optimizing the coating quality can be found . With regard to the influence of the gap distance on the coating quality, reference is made to the work of [9], [13], [16]. For increased gap distance within the stable coating window, a tendency to increase the wet film height was found, which is accompanied by a narrower width due to the constant volume flow. In addition, stronger edge effects are observed.

The effects of a higher angle of attack (converging gap in process direction), as shown in [9], [10], point in the opposite direction. The wet film becomes wider and thinner due to the higher shear forces between slot die and substrate. The angle of attack has a particularly strong effect on the edge effects, so that increasing the angle of attack tends to result in less edge elevation. This stronger effect on edge elevation compared to gap distance is of particular interest, as it allows for a more nuanced influence on each variable. The relationships are summarized in the Table 1.

Table 1: Oualitative effects of the control variables

	wet film heigth (h)	**wet film width** (b)	**edge elevation** (j)
increased gap (G)	↑	↓	↑
increased angle (α)	↓	↑	↓↓

The identified variables and their interactions result in the schematic diagram for the controller, as shown in Figure 4. A multivariable controller with three input variables and two output variables is constructed. All three input variables affect the two output variables.

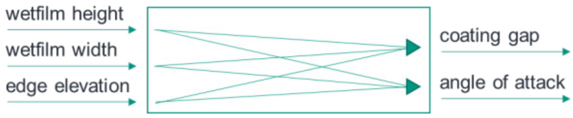

Figure 4: Concept of resulting multi variables control

3.2. Control Variables and Linguistic Terms

For the fuzzy controller linguistic terms are defined for the input and output variables. In general, these can be divided into positive (*P*), negative (*N*), and zero or neutral (*ZO*). For a further subdivision into five levels, the terms small (*S*) or large (*L*) are added to the positive and negative terms. This results, for example, in the classification *PL*. A natural language term is assigned to each level of variables. This is to ensure comprehensibility and easy creation and interpretation in the fuzzy controller. An excerpt of terms defined for the specific variables are shown in Table 2.

Table 2: Linguistic term for the input variables wet film height and wet film width as well as the output variable coating gap distance.

	NL	**NS**	**ZO**	**PS**	**PL**
wet film height	very thin film	thin film	optimal height	thick film	very thick film
wet film width	very narrow film	narrow film	optimal width	wide film	very wide film
coating gap control	strongly reduce gap	reduce gap	constant gap	increase gap	strongly increase gap

The linguistic terms are assigned a degree of membership (μ) between 0 and 100 % in the translation. This allows a smooth transition between the terms and means that two terms can be active in the transition area, each with a degree of membership of less than 100%. For more detailed information, please refer to the more specific literature [17], [18]. As an example, the membership function of all terms for the deviation of the wet film height with a tolerance of ± 2.5 μm is shown in Figure 5.

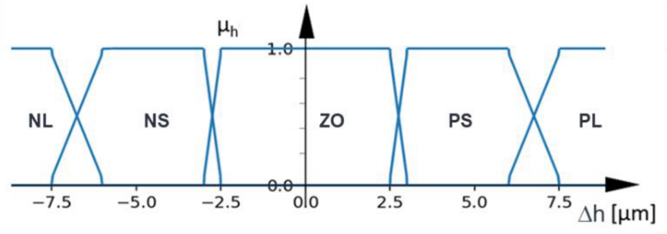

Figure 5: Membership functions (μ) of the linguistic terms of the deviation of the wet film height (Δh)

3.3. Rule Basis

For each combination of input variables, corresponding rules are derived from expert knowledge. With the three available input variables, 75 rules (5x5x3) are defined for the two output variables. The rules can be expressed in natural language in the form: "For thin film, low edge elevation, and optimum coating width, reduce the gap distance and keep the angle of attack constant". Example rules for the optimum coating width are shown in Table 3. Corresponding tables exist for each of the five terms of the wet film width. These rules based on the expert knowledge represent the core of the controller and consist on this qualitative level of general terms, which are correct for a wide range of slurry properties as considered in the corresponding sources in chapter 3.1.

Table 3: Rule basis with constant optimal wet film width (*ZO*)

Δh / Δj	**NL**	**NS**	**ZO**	**PS**	**PL**
ZO	$\Delta G \rightarrow PL$ $\Delta\alpha \rightarrow NL$	$\Delta G \rightarrow PS$ $\Delta\alpha \rightarrow NS$	$\Delta G \rightarrow ZO$ $\Delta\alpha \rightarrow ZO$	$\Delta G \rightarrow NS$ $\Delta\alpha \rightarrow NS$	$\Delta G \rightarrow NL$ $\Delta\alpha \rightarrow NL$
PS	$\Delta G \rightarrow PL$ $\Delta\alpha \rightarrow NS$	$\Delta G \rightarrow PS$ $\Delta\alpha \rightarrow ZO$	$\Delta G \rightarrow ZO$ $\Delta\alpha \rightarrow PS$	$\Delta G \rightarrow NS$ $\Delta\alpha \rightarrow ZO$	$\Delta G \rightarrow NL$ $\Delta\alpha \rightarrow NS$
PL	$\Delta G \rightarrow PL$ $\Delta\alpha \rightarrow ZO$	$\Delta G \rightarrow PS$ $\Delta\alpha \rightarrow PS$	$\Delta G \rightarrow ZO$ $\Delta\alpha \rightarrow PL$	$\Delta G \rightarrow NS$ $\Delta\alpha \rightarrow PS$	$\Delta G \rightarrow NS$ $\Delta\alpha \rightarrow ZO$

4. Evaluation of the Controller Behavior

In the next step, the behavior of the controller is visualized and the runtime of the program is classified. This is done to allow a comparison with the expert knowledge from chapter 3. The runtime is also checked against the specification of 0.1 s.

4.1. Mapping of Expert Knowledge

To illustrate the behavior of the controller, Figure 6 shows the correction of the gap distance and angle of attack as a function of the deviation from the target wet film height for a given edge rise and coating width. This corresponds to the line of *Δj = PS* from Table 3. It can be observed, that the controller cannot come to a standstill in this range, since it is not proposed to maintain both manipulated variables constant at any value of Δh *(ΔG = Δα = 0*). This can be considered correct, since the edge elevation is set as high (*PS*) and therefore outside the target range. For the gap distance, a monotonically increasing curve can be observed over the deviation of the wet film height. For the angle of attack, a higher angle is suggested for the optimum wet film height to compensate for edge elevation. If the wet film height deviation is too high, the angle is still reduced, which can be seen as a prioritization of the wet film height. This is also consistent with the initial rules and the qualitative approach from the expert knowledge.

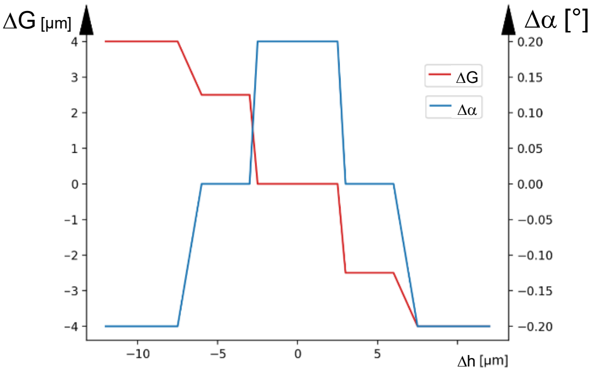

Figure 6: Proposed correction steps for high edge elevation (Δj = PS) and optimum film width (Δb = ZO) depending on the deviation of the wet film height

4.2. Runtime

To evaluate the runtime of the Phyton program, the time for one control cycle is measured. The values shown in Figure 7 refer to the runtime of a single control step. They do not include the initialization of membership functions and rules, which is performed once at program start. Since initialization only needs to be performed once at startup or when a parameter is changed, it is not considered runtime critical. No special hardware was used, but the program ran on a computer with moderate performance (Windows 10, i5-9200 U, 8 GB RAM). As expected, the highest average computation time of 0.04s is achieved with multiple active rules resulting from multiple active membership functions. This was considered in scenario 2. For scenario 3, the input variables were chosen so that only one linguistic term is active at a time. This means that the fewest rules are active and the number of computational steps is reduced. It shows that if all input variables can be translated into unambiguous linguistic terms, the runtime is lowest. Scenario 1 contains 100 randomly generated values and achieves runtimes of 0.035 s on average, placing it between Scenario 1 and Scenario 2. Due to the narrow ranges of the membership functions, the majority of the generated values are clearly in a linguistic term (compare the membership function in Figure 5) and therefore near to scenario 2. The runtime for random values is therefore in the middle range. Overall, the values can be considered sufficient for the purpose of the application and show the expected tendencies.

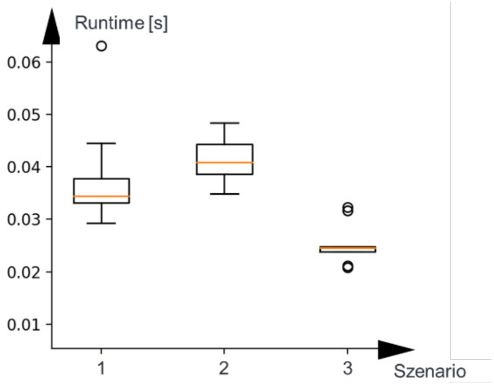

Figure 7: Runtime of the implemented fuzzy controller for random input (1), two active terms for each input variable (2) and one active term for each input variable (3)

5. Conclusion and Outlook

A fuzzy logic controller was constructed and its behavior was compared with the underlying expert knowledge. It was shown that the expert knowledge is represented qualitatively correctly by the rules. The achieved runtime of the Phyton program of about 0.02 - 0.05 s is already sufficient. With the concept presented here, a simple transferability can be guaranteed, since the core of the controller in the form of the formulated rules, as taken from the expert knowledge, can be retained in qualitative form for different materials, speeds or electrode thicknesses. An update of the membership functions according to changing tolerances for new products is assumed to be a justifiable effort.

For further evaluation of the controller, it will be integrated into the test setup. In particular, the interfaces and the real controller behavior are considered. The convergence behavior in real operation is to be compared with the behavior shown here and the number of necessary controller iterations at different starting points is to be determined. Optimization of the membership functions may be useful. An adjustment of the control basis is currently not considered necessary or useful.

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Appendix A. Excerpt from the program code

```
# Create an element of the class 'rule' with
if- and then-list
if_NL_ZO_ZO_then_PL_NL = rule(([mu_h_NL,
mu_j_ZO, mu_b_ZO]),([mu_G_PL, mu_alpha_NL]))

# Array of all membership functions of the
deviation of measured variables
mfunct = ([mu_h_NL, mu_h_NS, mu_h_ZO, mu_h_PS,
mu_h_PL, mu_j_ZO, mu_j_PS, mu_j_PL, mu_b_NL,
mu_b_NS, mu_b_ZO, mu_b_PS, mu_b_PL])

# Assignment of the current control deviations
to the membership functions
 for i in mfunct:
        if i.var == h:
            i.var_actual = h_actual


# Determine the activation level of each rule
and save in array H
  for i in arrayAllRules:
        if i.getH() > 0.0001:
            arrayH[j] = i.getH()

# Calculation of the scaled modal value of the
active rules
  for i in arrayModalvalueG:
       arrayModalvalueScaledG.append(
       arrayClippedG_   H[j] *
       arrayModalvalueG[j])

# Defuzzification into sharp control values
  for i in arrayModalwerteScaledG:
        sumModalScaledG = sumModalScaledG +
        arrayModalwerteScaledG[j]
```

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