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Concept for modelling the influence of electrode corrugation after calendering on stacking accuracy in battery cell production

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Abstract

Due to the complex process chain in battery cell production, effects of processes on subsequent processes must be evaluated. As challenge in calendering electrodes, corrugation can be observed depending on adjusted parameters. To evaluate the corrugation with regard to the subsequent stacking process accuracy, a concept for modelling the process chain calendering - separation - single sheet stacking is presented. First, an experimental approach for modelling the calendering impact on the electrode sheet geometry after separation is suggested. Finally, a FEM simulation approach for the single sheet stacking process is presented, which is suitable to model impacts from previous processes.

Keywords: Modelling; Finite element method (FEM); Manufacturing system

1. Introduction

On a global level, the demand for lithium-ion batteries can be expected to grow significantly. Electrified powertrains are being increasingly developed within the mobility sector, mainly driven by strict environmental regulations. Lithium-ion batteries are the only technology of mobile electrical energy storage which are currently capable for mass production as well as roughly meeting the high demands of customers [1]. In addition, the use of lithium-ion batteries is also becoming increasingly apparent in the field of stationary applications [2]. Rising sales markets as well as the cost sensitivity of customers are pushing production systems into the focus of research and industry. Due to a large variety of cell chemistries, their continuous optimization and upcoming developments, material systems often change from one product generation to the next, which must be able to get processed in the capital-intensive production systems despite different product properties. However, increasing quality requirements are affecting battery cell production as the lithium-ion battery is becoming a distinguishing feature of the later product [3]. Last but not least, format and material flexibility can be observed as a further demand on the production system [4]. These requirements lead to a variety of challenges in the development and operation of production systems for battery cells. The individual production steps of the prismatic and pouch cell, which are presented in Fig. 1, have a large range of possible process parameters which must be carefully adjusted to achieve the desired results. In addition, however, the process-structure relationships, i.e. the effects of the process parameters on the properties of the cell component, are still not fully understood. Furthermore, there is a pronounced dependence of the structural properties of cell components on previous processes [5]. In order to support machine manufacturers in the development of production systems and to reduce the commissioning effort by limiting the parameters, process simulations seem to be an appropriate tool. For this purpose, approaches for several process simulations as well as including effects of previous processes on the respective process can already be found in the literature, see [5-7]. Concerning the cell stacking process for prismatic and pouch cells and the influences of previous process steps on this

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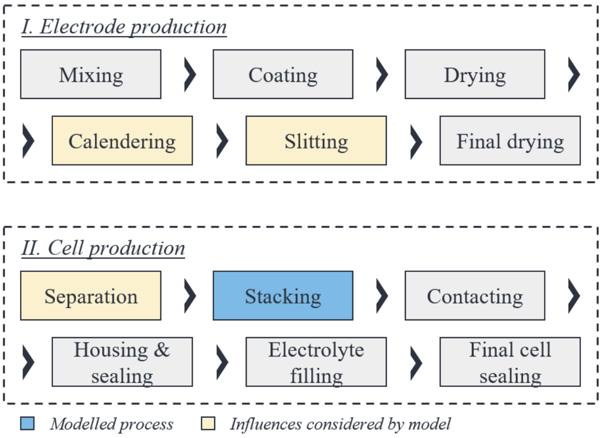

Fig. 1. Electrode & cell production of pouch and prismatic cells according to [8]

process, there are hardly any approaches in the literature. Such a model could enlarge the understanding of the general process and the influence of previous processes. Furthermore, it could support to define tolerances for processes and production facilities during the development phase. Therefore, an approach is presented to model the stacking accuracy of a cell stack after the stacking process. Influences from previous processes are considered with focus on geometric deviations of single sheet electrodes.

2. State of the Art

2.1. Calendering

In the calendering process, the anode and cathode are compressed by a pair of rollers with a defined gap in between. The purpose of compression is to adjust the porosity as well as the pore structure of the electrode coating in an optimal setting [9]. Since the structure represents the conductive paths for the later operation of the cell, calendering has a decisive influence on the final cell performance [9]. The process steps for separation are shown schematically in Fig. 2.

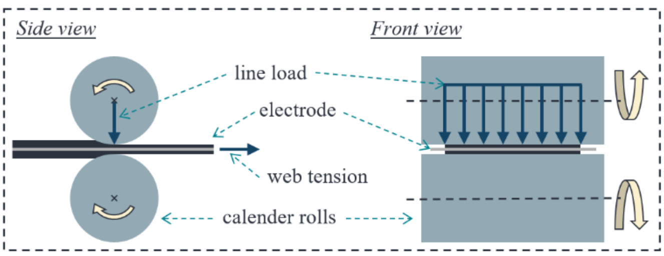

Fig. 2. Schematic calendering process according to [10]

With regard to the cell performance there is an optimum of the degree of calendering. However, undesirable effects occur to the electrodes at higher degrees. Günther et al. classify the effects basically into geometrical, structural and mechanical effects [11]. As the geometrical effects are the most influential for the stacking process, this paper will only focus on these. Bold and Fleischer do not subdivide the effects into the three classes, but like Günther et al. they describe the following effects [10,11]:

- Electrode corrugation
- Foil embossing
- Saber effect
- Corrugations at the coating edge [10,11]

Electrode corrugation describes the corrugations along machine direction which are formed in the electrode due to calendering. Günther et al. lists inhomogeneous density distribution in the electrode as the reason [11]. Foil embossing are wrinkles that form in the uncoated area of the electrode due to lateral side pressure of the coating during the calendering process. The saber effect results from the elongation of the electrode in the coated area opposed to the uncoated foil, which is not elongated since the calender rolls only have contact with the coating. Corrugations at the coating edge occur due to the greater coating thickness at the edge of the coating, the so called edge effect, which causes these areas to deform more. [10,11].

In literature, the effects are described in qualitative detail. However, depending on the parameter settings the effects are larger or smaller. The question arises which limits of the occurring effects are feasible for subsequent processes. Günther et al. only evaluate qualitatively the impact of the different effects on subsequent processes at the research production lab at TU Munich [11]. Due to the varying characteristics of the effects, it can be assumed that electrodes can be further processed to a certain level. However, there is still no approach known to quantitatively describe the effects on subsequent processes and to set limits for geometrical deviations of electrodes after calendering. For this purpose, the scientific paper presents an approach for modelling the influence of these effects on the stacking accuracy after the subsequent stacking process.

2.2. Separation

The separation of electrodes into single sheet electrodes is conducted in a three-stage process. First the electrode is cut in the running direction, which is called slitting. Then, in the so-called notching process, the conductor tabs and a small curvature at the edges are punched out. Finally, the actual separation into single sheet electrodes takes place by cutting them to the desired length. [12,13]

Baumeister and Fleischer present an alternative approach from the research side [14]. Here, the single sheets are punched from the whole electrode and then directly placed on the stack. The process of separation is thus combined with the stacking process in a cut-and-place-module. [14]

With regard to the separation mechanisms, punching is an established process. However, there are also alternative approaches that use laser cutting. Quality aspects for separation are a proper cutting edge and the avoidance of loose particles, which Jansen et al. describe in [15]. Furthermore, it must be ensured that the length and width dimensions of the electrode are kept within the tolerances. Investigations in this regard are presented by Weinmann et al. in [16]. As an explanation for deviating dimensions inhomogeneities in web tension are provided [16]. The investigations were carried out on the above-mentioned cut-and-place module [14,16].

In conclusion, it can be summarized that there are some research studies in the field of separation of electrodes into single sheet electrodes. However, no systematic investigations have yet been carried out to examine the effects of the geometric deviations after calendering on the resulting shape of the single sheet electrode.

2.3. Cell stack formation

In principle, there are continuous as well as discontinuous processes for cell stacking of prismatic and pouch cells [13]. In this paper, however, only the discontinuous processes will be considered, i.e. Z-folding with single electrodes and single sheet stacking. Therefore, only these will be presented in more detail based on [13]. First the electrodes are taken from the magazines. Then, they are placed on an alignment table and aligned by means of a camera system or mechanical actuator. From there they are moved to the stack usually by a vacuum gripper. Meanwhile, the stack is fixed with blank holders. The electrode is then placed on the blank holders with the aid of the gripper. Here, the low bending stiffness of the electrode is exploited. At the same time, the gripper serves as fixation for the stack, as the blank holders have to be repositioned in order to fix the uppermost electrode as well. Finally, the gripper moves back to the next electrode or separator. The two processes differ in that the electrodes as well as the separators are available as single sheets for single sheet stacking. In Z-folding with single electrodes the separator forms a 'Z' shape in which the individual electrodes are placed. For the process handling this implies that on the one hand the separator is handled differently and on the other hand the blank holders fix the stack in different process strategies. The schematic sequence of single sheet stacking is shown in Fig. 3. [13]

The quality requirements for the resulting stack are common to both processes. First of all, no damage must occur through the interaction of the gripper and the blank holder with the electrode or the separator, as this would lead to a malfunction

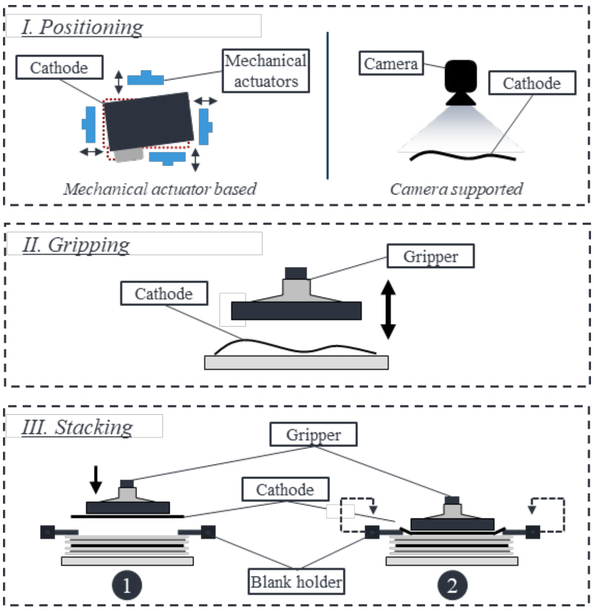

Fig. 3. Schematic single sheet stacking process according to [13]

of the battery cell [17]. Furthermore, it must be ensured that no particle contamination can occur during the process [17]. However, the essential, stand-alone quality feature in the stacking process is the stacking accuracy. Leithoff et al. show that a too large deviation of the stacking accuracy leads to a lower performance of the cells [18]. Baumeister and Fleischer as well as Kurfer et al. characterize their stacking system by the stacking accuracy that can be achieved [14,17]. With regard to the quantification of the stacking accuracy, there are various specifications which range from +/- 0.1 mm to +/- 0.5 mm for the permissible deviations of the side edges [19]. With regard to the orientation of the individual single sheets, +/- 0.5° are specified [19]. Mooy also deduces so-called tolerance areas around the coated corner points of the electrode from the listed positioning deviations [19].

To this day, stacking accuracy has been used as a tool for characterizing the stacking process and the associated equipment. However, there is no modelling of the actual stacking process known to predict the stacking accuracy and thus to support the development and commissioning of stacking systems for battery cell production. For this reason a method must be developed to model the stacking accuracy as a consequence of the effects after calendering and its impact by geometrical deviations after separation. The objective is to be able to obtain conclusions about tolerable deviations of previous processes with respect to the required stacking accuracy.

3. Development of a methodology for modelling the stacking accuracy

The starting point for the methodology is the shape of the single sheet electrode. Depending on the parameter settings of previous processes, shapes of different characteristics can be expected. For this purpose, an experimental set-up is first developed to record and characterize the shape of the single sheet electrode. Subsequently, a starting geometry for a finite element model can be derived based on characteristic deformations. Since the material characteristics of the electrodes change depending on the parameter settings of previous processes, material data must be acquired for the simulation model. For this purpose, it can be referred to methods of the literature, such as [20]. In order to describe the positioning of the electrode relative to the gripper before it is placed on the stack, the gripping process is first modelled and simulated via Finite Element Method (FEM). To describe the propagation of the inaccuracy introduced by the gripper-cathode-contact, the result of the simulation is passed on the actual FEM stacking simulation. The stacking simulation represents the interaction of the electrode with the blank holders. In combination with the precision of the stacking kinematics, the result of the stacking simulation is the achieved stacking accuracy of the produced stack. Subsequently, it can be concluded whether the desired stacking accuracy is sufficient, or whether the parameters of the previous process need to be adjusted. An overview of the presented method is shown in Fig. 4.

4. Impact analysis for shape characteristics of single sheet electrodes

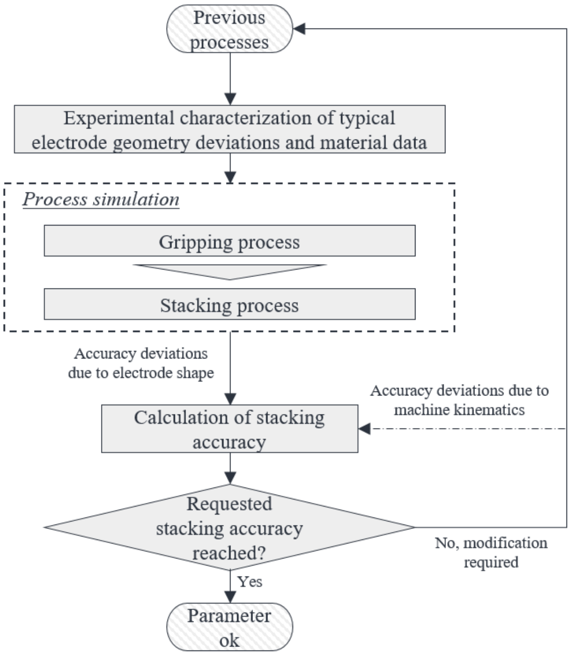

Fig. 4. Schematic procedure of the presented methodology

After describing the effects that can occur after calendering, an impact analysis can be made with regard to the geometric shape of the single sheet electrode. The analysis refers to the electrode contour as seen in Fig. 3.

In case of the electrode corrugation that exists in machine direction due to calendering, it can be assumed that this will propagate into the single sheet electrode, but will be less pronounced. It can be assumed that the corrugation will be more pronounced in the area of the conductor tab, because the electrode has been slightly elongated in machine direction on the opposite side of the conductor tab by the calendering process. However, the electrode is held together directly at the conductor tab by the uncalendered and not elongated foil. Within the remaining area of the electrode, it can be assumed that the electrode can spread uniformly when the uncoated foil edges are cut off.

If corrugations at the coating edge occur they can still be identified at the edge of the electrode after separation. As the rest of the electrode has not been plastically deformed so much, the corrugation at the edge of the electrode remains despite separation.

Due to the web tension that is applied during calendering, the electrodes are plastically deformed as a result of their stiffness when being wound onto the coil. In case of single sheets this occurs as a bending over the whole sheet with a specific radius. Depending on the stiffness of the calendered electrode, this effect is strongly pronounced or not at all. It can be assumed that the effect is at least reduced, since the electrode passes through a kind of straightening process before it is separated due to the web guidance.

Deviations in the web guidance due to the saber effect as well as general tolerances in the machine and equipment can lead to deviations in length and width dimensions.

In addition, it can be assumed that randomly distributed irregularities of the electrode shape occur due to coating thickness variations and locally deviating particle and binder concentrations.

In order to measure the geometric shape of single sheet electrodes an experimental setup was developed by using a GOM Atos Core 135 system. Due to the large surface area of the electrodes (~200 mm x 135 mm), reference points were placed around the contour of the electrode on a white, non-reflecting surface in order to record the entire shape of the electrode by taking several images. The experimental setup is shown in Fig. 5. As an example, a recorded Lithium iron phosphate (LFP) cathode can be seen, where the coil bending is clearly visible. The single sheet cathode was separated by means of strip steel cutting.

With several measurements, characteristic shapes can be determined depending on the parameter settings of previous processes. The characteristic shapes can then be transferred to

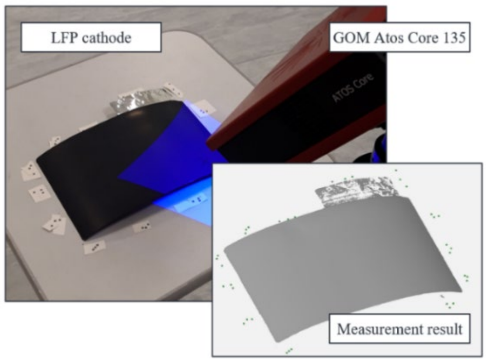

Fig. 5. Measurement setup and exemplary measurement of an LFP cathode with coil bending

the process simulation in order to predict the stacking accuracy that can be achieved with the deformed electrodes. Due to not yet completed experimental characterization of the single sheet electrodes, a theoretical electrode with corrugations at the coating edge as well as larger corrugations in the conductor tab area was constructed. The simulation will be demonstrated in the next section by using this example.

5. Modelling of single sheet stacking

In order to model the shape influence of the electrode on the stacking accuracy, a finite element method simulation was developed. In general, the input to the simulation model is the material model data and the geometric shape of the electrode, which was discussed in section 4. The output of the simulation is the spatial position of the electrode after interaction with gripper and blank holders. This information can then be used to deduce the stacking accuracy. As modelling environment Abaqus CAE was used.

5.1. Modelling setup and assumptions

To model the stacking accuracy, the single sheet stacking process is divided into two simulation steps:

1. Implicit simulation of gripping process
2. Implicit simulation of interaction of cathode with blank holders (stacking process)

The base plate, the gripper as well as the blank holders were modeled as discrete rigid bodies due to their high stiffness compared to the electrode sheet. The electrode sheet were modeled as shell with 1176 elements and with the element type S4R. The electrode was exemplarily modelled with a sine wave at the edge of the coating with a wavelength of ~ 26 mm and an amplitude of ~ 1 mm. On the opposite, a semi-sinusoidal wave with an amplitude of about 10 mm was modelled for electrode corrugation. The values were derived according to [11]. The two curves were connected by plane modelling in CAD System Siemens NX and then imported to Abaqus. Contact between the parts were modeled as penalty contact. For simulation step 1 it was assumed that the first contact point of the gripper with the electrode does not displace in x- and y-direction. Due to the surface that forms at the contact point, it was further assumed that the cathode at the contact point does not rotate around the z axis. Both assumptions a well as the movement of the gripper were realized by boundary conditions. For simulation step 2 the electrode is fixed by the gripper which was done by boundary conditions. The blank holders were moved to the position for fixing the electrode with boundary condition. Both steps were modeled with 1s step time. Fig. 6 provides a schematic insight into the simulation.

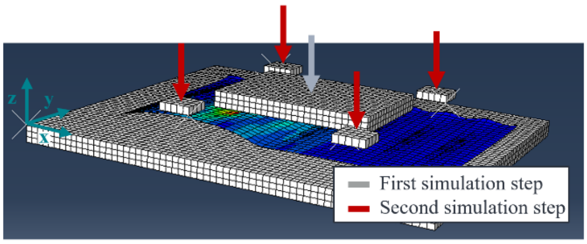

Fig. 6. FEM model for stacking process and simulation steps

For the modelling of the material behaviour, the electrode coated on both sides was modelled as a homogeneous material for an NMC-111 cathode. For this purpose, a linear-elastic material behaviour was used, since it was assumed that the cathode does not deform plastically during the process. The material data is based on [20].

5.2. Simulation of single sheet stacking

To visualize the exemplary simulation results, the relative displacement of the four nodes at the electrode corners is plotted over the simulation step time. For reasons of clarity only the displacements of the nodes in-plane, here x- and y-direction, are shown. Thus, in Fig. 7 two curves per node are shown.

The result of the simulation clearly shows that a displacement of the electrode can be observed depending on the electrode deformation. The position of the electrode edges and corners can now be compared with the required tolerances, which were discussed in section 2.3. A deduction can be derived whether the stacking accuracy can be achieved or not. Not yet included in this calculation are the initial positioning accuracy of the cathode and the inaccuracy of the kinematics in the stacking process. The results also illustrate the strong influence of the gripper on stacking accuracy. The blank holders have less influence on the stacking accuracy. However, it is reasonable to expect that the interaction of the electrode with the existing stack as well as the clamping strategy of the blank holders can influence the stacking accuracy. This has not yet been integrated into the existing simulation but is part of future research works.

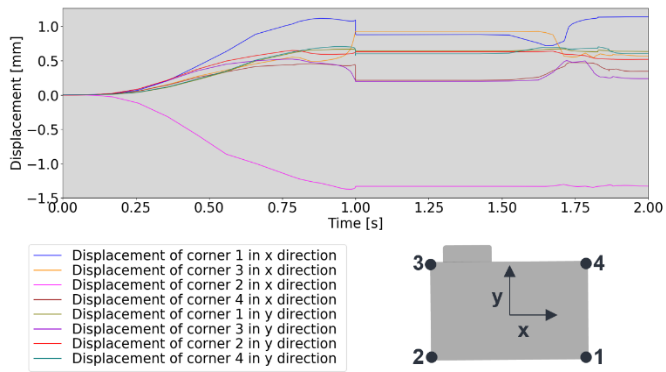

Fig. 7. Exemplary result of the process simulation

To sum up, the results give a first impression how corrugation can influence stacking accuracy. However, it is clear that the qualitative presentation of the method is the main focus here. To be able to make quantitative statements, the method must be validated first. An approach to this is shown in the following section.

5.3. Validation approach

The validation of the simulation is complex as the influence of the kinematics must be excluded or at least minimized. For this reason, no commercially available stacker can be used but a special test rig must be developed. Schematically the concept is shown in Fig. 8. In total, the test rig consists of three parking stations as well as two movable machine tables, each equipped with a zero-point clamping system. Due to the enormous precision of these coupling elements, it was decided to use this. The gripping table serves as an alignment platform for the electrode, which can be precisely placed there by means of a mechanical limit stop. With an exchangeable angle any tolerance deviations can also be taken into account. On the stacking table four blank holder actuators are mounted, which can be fixed anywhere in the plane. Furthermore, the parking station at the middle position has a single-axis kinematic with a vertically movable electrode gripper.

For validation the gripping table is first equipped with an electrode. Then this table is placed in the middle position under the kinematics. Following, the gripper picks up the electrode. The table is then changed under the gripper so that the stacking table is now underneath. The gripper can deposit the gripped electrode by a vertical movement and the blank holders can fix the electrode. The geometry of the electrode can then be

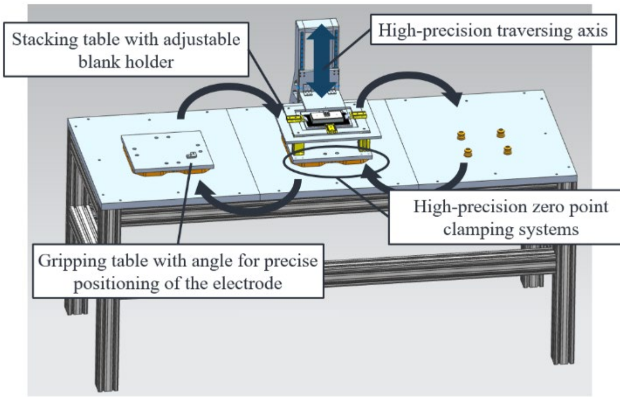

Fig. 8. Concept for validation test rig

recorded by using the GOM Atos Core 135 measuring system. With this setup, the deformation influence of the electrodes on the stacking accuracy can be measured extremely precisely.

6. Conclusions and Outlook

First, an impact analysis was carried out to determine the effect of geometrically deformed electrodes after calendering on the geometry of single sheet electrodes. Subsequently, an experimental setup was presented to investigate the geometry. Based on this, an approach was proposed to model and simulate the stacking process and its stacking accuracy by using the finite element method. Finally, an approach to validate the simulation by means of a specially developed test rig was presented.

The model enables to investigate the effects of previous processes on the stacking accuracy. Furthermore, it can be used to optimally design the stacking machine with regard to tolerance management during the development process. It can also provide support during commissioning in order to quickly find optimum parameter settings. In future, the model has the potential to provide training data for AI models, which can be used to predict the stacking accuracy inline based on the electrode geometry. This could reduce the need for expensive measuring equipment.

Since the focus was on the presentation of the methodology, the next step is the validation. Last but not least, the extension of the simulation to include the interaction of several electrodes in the stack is a further aspect of future works as the concrete geometry of the stack can be of interest for subsequent processes such as electrolyte filling.

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