Enhanced Deposition Accuracy for Battery Electrodes in a Novel High-Speed Stacking Process

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Abstract

Due to the increasing demand for lithium-ion battery cells, the cell production processes face substantial challenges to increase productivity. Among these production processes, the assembly of electrode-separator-compounds is very relevant regarding the value added towards the production chain. However, it also represents a productivity bottleneck due to the time-consuming nature of conventional stacking processes. A novel assembly process with a rotational handling unit and continuous material flow has a significant potential to decrease the influence of this bottleneck process and to enhance the overall productivity of the production chain. However, the alignment of the electrodes within the compound is challenging. This work systematically identifies alignment principles for high-speed assembly processes in general, and for the novel assembly process in particular. By transferring the selected principles to the rotational process, suitable alignment mechanisms are developed for the assembly system. Due to their modular design, the mechanisms can be adapted to the positioning requirements of the relevant process phase and the electrode type. Consequently, the positioning mechanisms are suitable for both pre-/coarse-positioning and fine positioning and can be applied for anode, cathode, as well as laminated intermediate products. An experimental validation describes the effectiveness of the developed mechanisms for the alignment within the electrode-separator-compound for different types of electrodes. Overall, the introduction of alignment mechanisms in the assembly system leads to enhanced deposition accuracy and contributes to establishing the novel stacking process in an industrial context.

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Keywords: Configurable Assembly Processes; Handling; Lithium-Ion Battery Production; Cell Assembly

1. Introduction: Challenges of electrode stacking

1.1. Challenges of electrode stacking

Recently, lithium-ion batteries face a strong demand, leading to an increase in the production capacities of the battery cells. The main component of a battery cell is the electrode-separator-compound (ESC) with positive and negative electrodes – anodes and cathodes – and the separator placed in between. Electrodes consist of a thin current collector foil, aluminium for the cathode, copper for the anode, with a 150 µm thick, two-sided coating of active material [1]. The separator is a thin polymer-film with a thickness of 25 µm or less. The assembly

<table>
<thead>
<tr>
<th>Nomenclature</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESC</td>
<td>electrode-separator-compound</td>
</tr>
<tr>
<td>H\textsubscript{ST}</td>
<td>Height of the stacking table</td>
</tr>
<tr>
<td>L\textsubscript{X,Y}</td>
<td>Length and width of electrode</td>
</tr>
<tr>
<td>ΔL\textsubscript{X,Y}</td>
<td>Separator overlap</td>
</tr>
<tr>
<td>n</td>
<td>Number of paddles</td>
</tr>
<tr>
<td>Δp</td>
<td>Differential pressure of pneumatic handling systems</td>
</tr>
<tr>
<td>v</td>
<td>Rotational velocity of the paddle wheel axis</td>
</tr>
<tr>
<td>W\textsubscript{P}</td>
<td>Width between the paddle guiding elements</td>
</tr>
<tr>
<td>W\textsubscript{ST}</td>
<td>Width between the rotating end stop</td>
</tr>
<tr>
<td>X,Y,Z</td>
<td>translational degrees of freedom</td>
</tr>
<tr>
<td>A,B,C</td>
<td>rotational degrees of freedom</td>
</tr>
</tbody>
</table>

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process of the ESC is crucial, as it directly relates to the cost of the cells. A significant increase in productivity leads to cost reduction [1] and enables the stacking process to catch up with the highly productive roll-to-roll electrode production [2]. However, the quality of this process strongly influences the performance and safety of the battery cell. Hence, there are three main evaluation criteria for the ESC assembly: the deposition accuracy, the gentle handling of the thin, delicate materials and the productivity. The deposition accuracy is crucial for the electrochemical performance and safety of the battery [3]. Within the compound, the anode circumferentially overlays the cathode to assure a full cover of the cathode active material [3]. Furthermore, the separator circumferentially overlaps the anode to assure a full cover of the anode and to avoid short circuits. The gentle handling especially refers to the reduction of particle contamination and mechanical stresses. Mechanical stresses can induce damages such as cracks or delamination of the coating, especially when handling thick electrodes [4, 5]. Cross-contamination of coating particles is a source for short circuits. To mitigate this risk, a strict separation of materials before the assembly process is required [6].

Currently three technologies dominate the ESC assembly process: winding, z-folding and stacking. Stacking and z-folding are less productive than winding, but also have advantages regarding reduced mechanical stresses and higher energy density compared to winding [4, 7]. The state of the art for electrode stacking is a robot-based pick-and-place process, with one robot for each cathode, anode and separator and discrete sheet material. Z-folding applies pick-and-place processes for the electrodes, while it feeds the separator in a continuous web. A further increase in productivity for pick-and-place based processes is hardly achievable due to a high share of acceleration/deceleration, forward/reverse and non-value adding unladen movements [9]. Consequently, novel processes need to be developed for enhanced productivity compared to pick-and-place processes.

1.2. The paddle wheel mechanism for stacking

As an alternative to pick-and-place processes for stacking thin, limp objects, different approaches are described in research or are established in industrial use cases, which could be transferred to electrodes. These approaches apply two main strategies to enhance the stacking speed: (1) continuous (rotating or oscillating) movements [8, 9] and (2) parallel handling of multiple objects or parallel process steps [10, 11, 12]. The present study focuses on the concept of a paddle wheel, a handling and stacking mechanism applied for currency discrimination and other small or flat objects [13, 14, 15]. The mechanism consists of a rotational handling unit with several paddles arranged around a hub and its periphery. The mechanism combines the two mentioned strategies: (1) The paddles pick-up and release electrodes continuously (“on the fly”) with alternate anodes and cathodes. (2) The wheel handles several anodes, cathodes and separators at the same time within its multiple paddles with a handling rate per electrode of

\[
\text{Handling rate } [\text{s}^{-1}] = \frac{n [\text{electrode}] \times n}{360^\circ}
\]  

A scale-up of the process is achieved by increasing the number of paddles \(n\) and/or the rotational velocity \(v\). Consequently, the stacking speed is no longer related to the (limited) acceleration/deceleration of the pick-and-place axis.

A further increase in productivity is achieved by preliminary lamination of the separator on either cathode or anode. The laminated intermediate products are more robust compared to the delicate separator sheets and reduce the number of handling objects [16]. Additionally, the laminated separator covers the coating of one type of electrode, which effectively inhibits cross-contamination and allows production areas and handling devices to be shared for anodes and cathodes. This effectively achieves a strict separation of anode and cathode materials.

The application of the described mechanism results in a five-stage stacking process (Fig. 1): First, a conveyor belt inserts the handling object (electrode or laminate). Second, one paddle picks up the handling object. The pick-up process is complete, when the handling object lies on the paddle. The paddle transports the handling object in a rotational motion during the third phase. At a defined rotational position, the ejection of the handling object is initiated. The handling objects slides from the paddle and vertically descends on the stacking table. The process kinematic and resulting electrode motion are further explained in [17]. The paddle wheel mechanism is generally described for electrode stacking [15, 18]. Still, the requirements of electrode handling, as described in Ch. 1, represent three basic challenges to be solved in order to integrate the paddle wheel mechanism into an industrial stacking process: sufficient deposition accuracy, gentle handling and high productivity. The process easily meets the requirement of productivity by pursuing the strategies of continuous movements and parallelisation. Regarding the requirement of gentle handling, recent publications address effective measures to mitigate the mechanical loads on the electrode during the process, e.g.,

![Fig. 1. Process phases of the novel stacking process and supports of the electrode during the process phases, modified version of [22]](image-url)
optimized tuning of the process, as well as an appropriate choice of the paddle material and geometry [5, 17, 19]. These can be implemented into the process as required. However, the deposition accuracy is a challenging requirement for a stacking process based on the paddle wheel mechanism. The objective of the present research is to systematically explore, select and evaluate solutions for enhanced deposition accuracy in the paddle wheel process for a time-efficient and gentle handling.

2. Exploration of strategies for electrode deposition

To improve deposition accuracy, a precise manipulation of the electrode position is required during all process phases. Pick-and-place processes usually integrate a distinct positioning step based on image-based object detection after pick-up and an adjusted place-position in the process sequence, leading to a displacement error under 1 mm [3], but increasing complexity, especially regarding the process sequences, and cycle times. An adjusted place-position to compensate a positioning error during pick-up is not applicable for the paddle wheel due to parallel handling of multiple electrodes with consequent error propagation. Therefore, other general physical principles which relate to mechanical, pneumatic or field forces are investigated and linked to strategies for handling, manipulation and release of electrodes and laminates. Suitable strategies combine the requirements of gentle handling, continuous movement and parallel handling (Table 1).

Pneumatic principles use a gaseous medium with positive or negative pressure difference $\Delta p$ to manipulate objects. Area vacuum grippers apply a uniform negative $\Delta p$ to handle electrodes, minimizing applied stresses [6]. However, the generation of suction forces is time-consuming. Nozzles [20] or ultrasonic emitters [21] operate with a positive $\Delta p$ to manipulate electrodes at high speed. This creates fast flowing air streams, inducing particulate emission and leading to contaminations of the electrode surfaces [6]. Field forces relate to different physical effects. The simplest effect is gravity and is especially relevant for the ejection phase. However, the gravity-based release process is highly sensitive to air flow and aerodynamic resistance. Field forces based on electrostatic or Van-der-Waals effects are commonly applied for light objects, e.g., micro-electronics. These principles usually require a time-consuming release strategy like ionisation (electrostatic) or shear forces (Van-der-Waals). Additionally, the gripping characteristics depend on the material properties of the handling object, e.g., the surface structure, and differ for anode and cathode [20, 22]. Mechanical principles relate to frictional forces or form fit applied by fixed or actuated end stops [20]. Frictional forces tend to ablate particles of the electrode coating. Additionally, the release in a high-speed process is unpredictable due to stick-slip effects. Therefore, the principle of form closure is to be preferred. Passive principles are best suited for high-speed applications. However, their behaviour usually cannot be altered during the process in order to adapt to different materials. Therefore, in order to efficiently align multiple types of handling objects – anode, cathode and laminates – with different handling characteristics, e.g. weight or size, active principles are required. As a result, passive principles should be applied to individual paddles in order to handle a single type of electrode, whereas active principles are used to handle multiple different electrodes on the stacking table.

During the handling in the wheel, the electrode performs an unguided movement. This results in a lack of supports in at least one direction and an imbalance of forces, moments and reactions, which are schematically visualized in the free body diagram (Fig. 1). The high degrees of freedom, especially during the pick-up and ejection phase with fully unguided movement, represent a potential source for deposition errors. This is a significant difference to current stacking processes, where a gripping or clamping force is permanently applied to keep the electrode in place. To improve the positioning of the electrode on the stacking table, it is crucial to increase the number of supports during various process phases by implementing one of the described positioning strategies. Ch. 3 presents suitable mechanisms to implement additional supports for the electrode. In this work, positioning strategies for the discussed phase 3 relate to pre- or coarse positioning, while final positioning takes place in phases 4 and 5.

Table 1. Applicable (✓) and non-applicable (✗) positioning principles for the high-speed process.

<table>
<thead>
<tr>
<th>Principle</th>
<th>Strategy (example)</th>
<th>Continuous movement</th>
<th>Parallel handling</th>
<th>Gentle handling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sequence-based principle</td>
<td>Compensation value</td>
<td>Adjusted place-position</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Physical principle Mechanical active</td>
<td>Rotating end stop</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Mechanical passive</td>
<td>Friction</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Pneumatic</td>
<td>Ultrasonic</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$\Delta p &gt; 0$</td>
<td>Area vacuum gripper</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Field forces</td>
<td>Electrostatic or Van-der-Waals</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

3. Evaluation of strategies for electrode deposition

3.1. Materials and settings for the experimental evaluation

In this study, electrodes and laminates in BLB2 format [3] (anode: $L_x=110$ mm, $L_y=150$ mm; cathode: $L_x=105$ mm, $L_y=145$ mm) are examined (Fig. 2). The anode material is a 10 $\mu$m Cu-substrate with 9.2 mg/cm$^2$ graphite on both sides. The selected cathode material was NCM622 with 17.3 mg/cm$^2$ mass loading per side on a 15 $\mu$m Al-substrate. Comparing the handling characteristics of both electrodes, the cathode is stiffer due to its high mass loading, while the anode with its graphite surface is slippery and is subject to a higher risk of abrasion. Given the tab (anode: 20x30 mm$^2$; cathode: 22.5x30 mm$^2$), the electrode’s centre of mass $cm_e$ deviates from the centre of mass of the coated surface $cm_C$ (anode: $\Delta X=0.6$ mm, $\Delta Y=1.96$ mm;
cathode: \(\Delta X=0.02\ \text{mm}, \Delta Y=0.11\ \text{mm}\). The laminated ESC are prepared with a lamination temperature of 100 °C and a lamination pressure of 20 Nmm\(^{-2}\) according to [18]. As a separator, a 20 \(\mu\)m trilayer separator (PE-PP-PE) with both-side 1 \(\mu\)m PVDF coating is used. The separator sheets are equally sized for cathode and anode laminates with \(L_{X,S}=115\ \text{mm}\) and \(L_{Y,S}=156\ \text{mm}\). This leads to circumferential overlaps of \(\Delta L_X=2.5\ \text{mm}\) and \(\Delta L_Y=3\ \text{mm}\) (anode laminate) and \(\Delta L_X=5\ \text{mm}\) and \(\Delta L_Y=5.5\ \text{mm}\) (cathode laminate). With increased \(\Delta L_{X,Y}\), the separator overlap becomes more fragile.

The parameters for the experimental evaluation are set based on geometrical prerequisites of the test rig and the handling objects (full factorial testing). The investigated parameters refer to the width \(W_P\) between the paddle guiding elements, the width \(W_{ST}\) between the rotating end stops and the height \(H_{ST}\) of the stacking table as shown in Fig. 3 and described in detail in sections 3.2 and 3.3. The minimum value for \(W_P\) depends on the lamination. While electrodes are guided tight with 1 mm gap on each side (anode: \(W_{P,\text{min}}=112\ \text{mm}\); cathode: \(W_{P,\text{max}}=107\ \text{mm}\)), laminates require a 1.5 mm gap to avoid a wedging behaviour during insertion (\(W_{P,\text{max}}=118\ \text{mm}\)). The maximum value \(W_{P,\text{max}}\) is 120 mm to avoid the collision of the guiding elements with other components of the test rig. \(W_{ST}\) is related to the size of the handling objects. Therefore, it is set as \(W_{ST,\text{min}}=L_X\) and \(W_{ST,\text{max}}=L_{X,S}\). The stacking table is raised and lowered by a linear axis with a stroke of 15 mm. At the height \(H_{ST,\text{max}}\), the stacking table is positioned to the maximum height without colliding with the paddles or the rotating end stops. As a result, the lowest position \(H_{ST,\text{min}}\) relates to \(H_{ST,\text{max}}\) minus the axis stroke. In Fig. 3, the parameter settings \(W_P=W_{P,\text{min}}, W_{ST}=W_{ST,\text{min}}\) and \(H_{ST}=H_{ST,\text{max}}\) are illustrated.

Finally, the insertion velocity is set to 1050 mm s\(^{-1}\) and the rotational velocity is set to 135° s\(^{-1}\). This corresponds to a stacking rate of 6 electrodes/laminates per second. The deposition quality was evaluated as described in Appendix A.

3.2. Strategies for pre- and coarse-positioning

At the beginning of the insertion phase, the electrode or laminate performs a fully unguided movement with six degrees of freedom before encountering the paddle wheel. The unguided movement takes place at a high speed to assure a complete insertion within the given time span [18]. Mechanical end stops such as guiding rails or slides decelerate the electrode or laminate during this phase, increasing the risk of an insufficient insertion speed. Consequently, the first manipulation takes place during the transportation phase. In this phase, the electrode or laminate is kept in the paddle with no alignment in the X-direction. To restrict the movement, guiding elements are introduced in the paddles and serve as mechanical end stops (\(W_P\), Fig. 3a). The guiding elements are arranged close to the electrode or laminate edges, restricting movements in X- and A-direction and leading to a more precise positioning on the paddle. As the electrode or laminate already encounters the guiding elements during the insertion phase, low tolerances decelerate the electrode or laminate and lead to wedging in the paddle. This compromises the insertion or ejection. Consequently, a trade-off is required between a narrow gap between the electrode or laminate and the guiding elements (\(W_{P,\text{min}}\)) for a sufficient X-and A-alignment and a wider gap (\(W_{P,\text{max}}\)) for free insertion and ejection. Based on the experimental results, a narrow gap is recommended for the cathode and anode laminate. On the contrary, anode and cathode laminate favour a wider gap for improved deposition accuracy (Fig. 4). Both favour wedging behaviour due to the low bending stiffness of the anode and the significant separator overlap \(\Delta L_{X,Y}\) of the cathode laminate. The separator overlap of the anode is smaller and therefore less flexible and fragile. Therefore it can be guided with \(W_{P,\text{min}}\) more accurately.

3.3. Positioning mechanisms for the ejection and deposition

During the ejection phase, the electrode is released from the paddle. It slides in Y-direction and sinks down onto the stacking table (deposition phase), where it is aligned in X-, Y- and A-direction. For the release, gravity or a mechanical end stop could be used. Merely relying on a utilization of gravity has several disadvantages for this application, as stick-slip-effects will cause an unpredictable release behaviour. Therefore, a mechanical end stop (ejection pin) is used to release the electrode. For a complete ejection, the pin impinges the electrode in Y-direction, fully pushing the electrode out of the paddles. Furthermore, the pin must not encounter the
electrode in Z-direction as this compromises ejection by lifting the electrode instead of pushing it out of the paddle. To foster a contact in Y-direction and inhibit a contact in Z-direction, the paddle is equipped with an end stop (paddle hook) close to the hub, which maintains a permanent gap between the electrode and the hub. The ejection pin is then shaped accordingly to fit in this gap and encounter the electrode horizontally (Fig. 3b). Apart from the ejection pin, there are still few supports during ejection to effectively limit the electrode movement, representing a potential source for deposition errors. By raising the stacking table (H\text{ST}, Fig. 3b), the duration of the ejection phase decreases, favouring an increased both rotational and translational deposition accuracy. The experimental results show a positive effect of a raised stacking table (H\text{ST,max}) for all types of handling objects.

After release from the paddle, a final alignment of the electrode takes place on the stacking table. For this application, actuated end stops with a rotating kinematic are applied (Fig. 3b). Similar to the positioning elements in the paddles (cf. Ch. 3.2), the rotating end stops reduce the range of motion of the electrode in X- and A-direction but also decelerate the electrode during the deposition movement and possibly impair the deposition accuracy in Y-direction. Consequently, similar results as for the paddle guiding elements were observed: cathode and anode laminate benefit from low tolerances of the positioning elements (W\text{F,min}) at the stacking table, while the limb anode and cathode laminate require higher tolerances (W\text{F,max}) for good Y-alignment to avoid wedging. Additionally, when the guiding elements are arranged too close to the target deposition, the electrodes ricochet, negatively affecting the X- and A-alignment. This effect was observed for all electrodes, but was strongest for the stiffer materials.

4. Conclusion

The experimental investigation proves the effectiveness of mechanical positioning mechanisms for enhanced alignment of anodes, cathodes and laminates. However, some conclusions for the process design can be drawn to make use of these positioning mechanisms more effectively.

The handling characteristics of the electrodes and laminates vary significantly. The anode is slippery and fragile due to its graphite coating. The anode laminate and the cathode are more robust. The circumferential separator overlap of the cathode laminate is also fragile. Hence, the effects of the applied positioning mechanisms depend on the type of handling object. To optimize the overall deposition quality, individual positioning mechanisms and machine parameters for anode, cathode and laminates should be considered. Regarding the guiding elements in the paddles, individual designs should be used for single types of handling objects. The radius R of the rotating positioning elements at the stacking table should be adjusted for the individual handling object accordingly, as exemplary shown as R\text{T} and R\text{C} (Fig. 3b). While individual measures are necessary for the positioning elements, raising the stacking table is beneficial for all handling objects.

Comparing the different types of electrodes and laminates, the alignment of the smaller cathode and the oversized anode laminate is more challenging than the anode and the cathode laminate. In the stacking process with alternating electrode and laminate as input material, it is recommended to utilize cathode laminates instead of anode laminates to improve deposition accuracies. This recommendation also applies to other stacking machines, e.g., to pre-align electrodes in a material buffer prior to a pick-and-place operation. Regarding other than the used materials and formats, e.g., other electrode formats or during the handling of fuel cell components, the alignment mechanisms are applicable after specifying the individual handling characteristics. However, the current paddle design is dedicated to a special format and the target manufacturing attributes of the mechanism are time, cost and quality, not flexibility.

With regard to all investigated strategies, the alignment during the ejection and deposition phase is significant for the final X- and A-position of the electrode, while the alignment during the transportation phase modestly contributes to the final X- and A-position. On the contrary, the guiding elements during the transportation phase influence the Y-alignment significantly due to deceleration and/or wedging of the electrodes and laminates. This can be observed even though the investigated positioning mechanism for the transportation phase exclusively limits the electrode motion in X-direction.

The experimental results also highlight the inferior accuracy in Y-direction compared to the X-direction. Consequently, further alignment strategies and consecutive studies should
focus on the Y-alignment, e.g., by optimizing end stops in Y-direction. However, when implementing new measures to limit the electrode movement, the accuracy in all three translational and rotational alignment directions have to be taken into account. Currently, the specified accuracy of 0.3 mm for industrial stackers with image-based object detection is still ahead of mechanical positioning mechanisms with a minimum deposition error of 1.2 mm (cathode laminates). By implementing additional alignment strategies, especially in Y-direction, the deposition accuracy of the lab scale demonstrator can further improve to close the gap to industrial stackers.

The examination of the deposition on the stacking table with an industrial camera is generally suitable for a quality control of the electrode position. However, in the industrial process, an artificial circle pattern applied on the electrode would not be tolerable. Therefore, the camera view needs to be improved to robustly detect the electrode edges, e.g., by adding light sources or flash.

The process dynamics and occurring contact forces have not been evaluated through complex simulations so far. This could be subject to further research and further optimization.

Acknowledgements

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Appendix A. Image acquisition and image processing

To evaluate the deposition accuracy, images of the handling objects are recorded on the stacking table directly after deposition by an industrial camera (Baumer VCXU-53M).

To prepare the electrodes and laminates for the image processing, a circle pattern was applied. For high contrasts, the dark coating of the electrodes was labelled with white circles while the white laminates were labelled with black circles. This assures a robust detection during the image processing, especially compared to the detection of the electrode edges that may be blurred due to shades. After image recording, the position of the electrode is extracted in a five-step image processing (Fig. 5): first, the region of interest (ROI) with the circle pattern is selected and the image is cropped accordingly. Second, several filters are applied to prepare the image for the feature extraction. In the feature extraction step, the circles are detected and two orthogonal regression lines are fitted on the circle pattern. As the extracted position of the circle relates to its centre, the image processing based on circle patterns is highly robust against geometric inaccuracies, blurred and shaded edges, especially compared to other patterns, e.g., checkerboard [23]. By means of the two regression lines, the position (pixel) and orientation of the electrode or laminate is detected afterwards. In the last step, the detected position is transformed from pixels to mm-coordinates.

References