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Simulation of the stacking process in battery cell manufacturing

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Abstract

Battery-electric drives become increasingly important in the context of electromobility, which means that battery cell manufacturing is assigned a key role from a production science perspective. Battery cell manufacturing consists of a complex sequential process chain, whereby the individual processes significantly influence the subsequent process steps. Especially for single sheet stacking of the electrode separator composite, the shape of the electrode sheets and their tolerances have a decisive impact on the achievable stacking accuracy. To quantify the influence, a simulation for the stacking accuracy is presented. First, a finite element simulation model is developed that calculates the achievable accuracy within the stacking process based on the sub processes positioning and gripping. With the simulation model shape deviations of the electrode sheets and their impact on the stacking accuracy are investigated. It is shown that length and width deviations in particular, as well as unevenness in the electrodes have an enormous influence on the achievable stacking accuracy. With the support of the simulation model, the stacking process can be examined in detail with regard to tolerable electrode shape dimensions and the required tolerances for this process step can be defined. This leads to a significant scrap rate reduction, especially in the ramp-up phase, which directly contributes to a more sustainable production of battery cells.

Keywords: battery cell manufacturing; stacking process; finite element method (FEM); simulation

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1. Introduction

Due to the electrification of automotive powertrains, the global demand for batteries has increased enormously. As a result, the battery cell manufacturing processes are being focused with regard to the output achieved, but also in terms of the achieved quality and the scrap rate. In order to optimize the above-mentioned aspects, great efforts are made to further develop the technology of the factory equipment with the associated machines and systems. An important process step for the manufacturing of prismatic or pouch battery cells is the stacking of the electrode-separator composites. Basically, there are various industrial processes such as Z-folding or single sheet stacking, which are used depending on the requirements [1–3]. Also on research side, innovative machinery for the stacking process has been developed in the past by research facilities, see [4–7].

An important parameter that affects all machinery is the achieved stacking accuracy. In literature, values between *+/- 0.2 mm* and *+/- 0.5 mm* are mentioned [8]. Weinmann examines the stacking process and its interactions in detail and structures them into individual problems [9]. The subsystems material guiding, separation, handling, alignment, joining and fixing are considered in detail and partly investigated experimentally [9]. The material guidance is investigated by means of an FE simulation model [9]. Further simulative approaches for material guidance can be found in Husseini et al. [10]. A first FE model for simulating the stacking process and the resulting stacking accuracy is presented by Mayer & Fleischer [2]. In the simulation model, the electrode gripping process and the

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interaction of the gripped electrode with the blank holders are investigated. However, the positioning process to align the single sheet electrode is not investigated [2].

Based on the analysis of the current state of the art, it appears that there is no approach yet that couples the electrode positioning with the gripping of the electrodes within the single stacking process and derives the achievable stacking accuracy from this. In addition, the electrode geometry, which is affected by tolerances, see [11], has only been partially and not systematically taken into account in previous simulations of the stacking process in literature. Exactly these two points are addressed in the present paper.

2. Approach for simulating the stacking process

The stacking accuracy is a quality-determining parameter in the manufacturing of electrode separator composites. However, this depends strongly on the tolerance-affected shape of the respective electrodes. In order to estimate which tolerances can be tolerated in the preceding process steps, a simulation model is therefore developed which calculates the stacking accuracy depending on the electrode shape. Here, the focus is the single sheet stacking process, which is detailed described in [2]. For this purpose, the process is first analyzed and boundary conditions are derived. The model approach of the simulation is then presented and simulation studies are conducted.

2.1. Process analysis und boundary conditions

Based on [2], the stacking process can be divided into the three process sub steps of positioning, gripping and the actual stacking process. First, the electrode is mechanically aligned and positioned by means of four sliders, each at an edge of the electrode. It is then gripped by a vacuum suction gripper and placed on the actual stack. Here, the gripper simultaneously locks the added electrode as well as the stack into position. The blank holders can thus release the stack and fix it again including the new electrode. It can be observed that especially the initial position of the gripper and the relative position of the electrode to the gripper contribute significantly to the stacking accuracy. It is assumed that the position of the electrode on the stack allows to assess the stacking accuracy sufficiently well. The reason for this is the assumption that the relevant accuracy deviations occur during the positioning and gripping process and not during the actual stacking process. Therefore, assessments of the positioning and the influence of tolerance-affected shapes on the gripping process is crucial. In order to evaluate the accuracy, the positions of the electrode corners are recorded and evaluated after the gripping process. In this way, a determination about the position of the electrode on the stack and how this affects the stacking accuracy can be made. As a boundary condition, it is assumed that the relative position of the electrode to the gripper does not change after the electrode has been picked up by the gripper. Furthermore, the model assumes a purely elastic material behaviour. The shapes of the mechanical alignment elements and the gripper are simulated as ideal, non-deformable geometries. Abaqus is used as simulation environment.

2.2. Model setup

An FEM simulation model was developed to investigate the stacking accuracy depending on the electrode shape. Part of the model is a table, where the electrode is placed. In addition, there are four mechanical aligners, which take over the alignment, whereby the positioning process can be simulated. Furthermore, there is an industry-typical gripper within the model. The mechanical alignment, gripper and table were modeled as rigid bodies, since their stiffness is significantly higher compared to the electrode. Only the electrode is modeled as a deformable body. Fig 1 shows a section of the developed simulation.

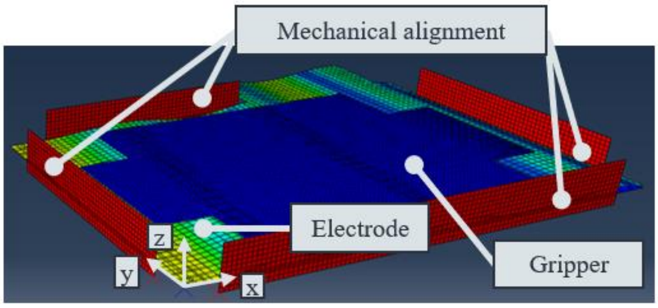

Fig 1. Model setup in Abaqus

In the simulation, the positioning process of an electrode is first simulated by means of the mechanical aligners pushing the electrode in position and second the gripping of the positioned electrode with a gripper. The actual stacking is not considered in this publication. The simulation was set up as a dynamic, explicit simulation. In detail, the model is divided into five simulation steps:

- Step 1: First, force of gravity affects the entire model and the electrode makes contacts with the table.
- Step 2: The aligners move to the table from the sides and align the electrode.
- Step 3: The gripper moves down and pushes the electrode on the table.
- Step 4: All elements remain in position so that possible vibrations can subside.
- Step 5: The aligners move away to the side and the electrode is held in position by the gripper.

All parts are modeled with shell elements, since their geometric dimensions in x- and y-direction are considerably larger than in z-direction. The electrode consists of about 9700 elements of type S4R. The investigated shapes of the individual electrodes are discussed separately in section 2.3.

To model the electrode, it is assumed that the electrodes, which actually consist of three layers (coating-substrate-coating), are considered as homogeneous bodies. However, substrate and active material have different material properties. For that reason, the electrode is modeled with three layers of S4R elements. The three layers are connected to each other by tie constraints. This allows the electrode to be assigned with different material properties for active material and substrate, which in combination better reflects the real behavior. For both materials ideal elastic behavior is assumed. Based on Zhang et al. the following values for the specific material parameters were assumed [12]. A Young's modulus of *25200 MPa* for the substrate and *609 MPa* for the active material were assumed [12]. Both materials are based on a Poisson’s ratio of *0.3*. The entire model was modeled with a coefficient of friction of *0.3*. A layer thickness of *0.92 mm* is assumed for the active material, and *0.020 mm* for the substrate [12]. For the substrate a density of *2.7 g/cm³* and for the active material a density of *3.0 g/cm³* were assumed. In order to investigate the achievable stacking accuracy, the position of the corners of the electrode is recorded at the start of the simulation and their path is followed through the entire simulation. From this, the final position of the electrode can be determined, which can then be compared with the ideal position and the permissible tolerance field.

2.3. Setup for simulation studies

To investigate the influence of the positioning and gripping process on the expected stacking accuracy, the parameters of the simulation study are explained. The basis for the study is the geometry of the electrode, which can be schematically seen in Fig 2.

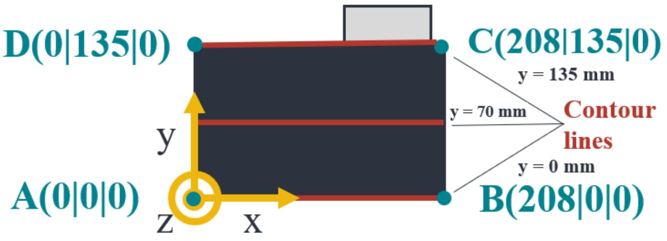

Fig 2. Corner point coordinates of the electrode in mm

Essential parameters to be investigated in this paper can initially be indicated by the coordinates of the individual corner points of the electrode. Depending on the characteristics of the coordinates, i.e. in accordance with possible tolerances from the previous process, geometric shapes such as parallelograms are created, whereby the nominal shape of the electrode is basically a rectangle. Furthermore, possible curvatures of the electrode, for example induced by the coil winding process before, can be modelled based on contour lines, see [11]. Table 1 shows the starting corner points of the simulated and tolerance-affected electrodes, from which the electrode shape can be derived. At the beginning of the simulation, the electrodes are positioned *2 mm* above the table. Subsequently, gravity force acts on the electrodes and establishes contact with the table. After the simulation has completed, the z-position of the corner points is recorded again in addition to the x- and y-position. The z-position is measured at the substrate layer.

Table 1. Initial position of the electrode corner positions.

<table>
<tr><th>Electrode ID</th><th>Point A</th><th>Point B</th><th>Point C</th><th>Point D</th><th>Pro-file</th></tr>
<tr><td>1</td><td>(-1|0|2)</td><td>(-207|0|2)</td><td>(207|135|2)</td><td>(-1|135|2)</td><td>flat</td></tr>
<tr><td>2</td><td>(-1/0/2)</td><td>(208/0/2)</td><td>(208/135/2)</td><td>(-1/135/2</td><td>flat</td></tr>
<tr><td>3</td><td>(-1/0/2)</td><td>(206/0/2)</td><td>(206/135/2)</td><td>(-1/135/2)</td><td>flat</td></tr>
<tr><td>4</td><td>(0/0/2)</td><td>(208/0/2)</td><td>(207/135/2)</td><td>(-1/135/2)</td><td>flat</td></tr>
<tr><td>5</td><td>(0/0,5/2)</td><td>(208/-0,5/2)</td><td>(207/134,5/2)</td><td>(-1/135,5/2)</td><td>flat</td></tr>
<tr><td>6</td><td>(0|0|2,27)</td><td>(208|0|2,44)</td><td>(208|135|2,14)</td><td>(0|135|2,3)</td><td>not flat</td></tr>
</table>

For a simpler, pictographic understanding of the experimental design, the electrodes are shown schematically in Fig 3. All electrodes except ID_6 were modeled flat, i.e. without curvature in z-direction.

For modelling electrode ID_6, the three contour lines with the corresponding z values were used, see Fig 4. The contour lines were modelled using the spline function in the CAD program Siemens NX and were arranged according to Fig 2. Subsequently, a surface was interpolated, the conductor tab was attached and the electrode was exported using a step file and fed to the simulation model. The values of the splines are based on the measurements from [11].

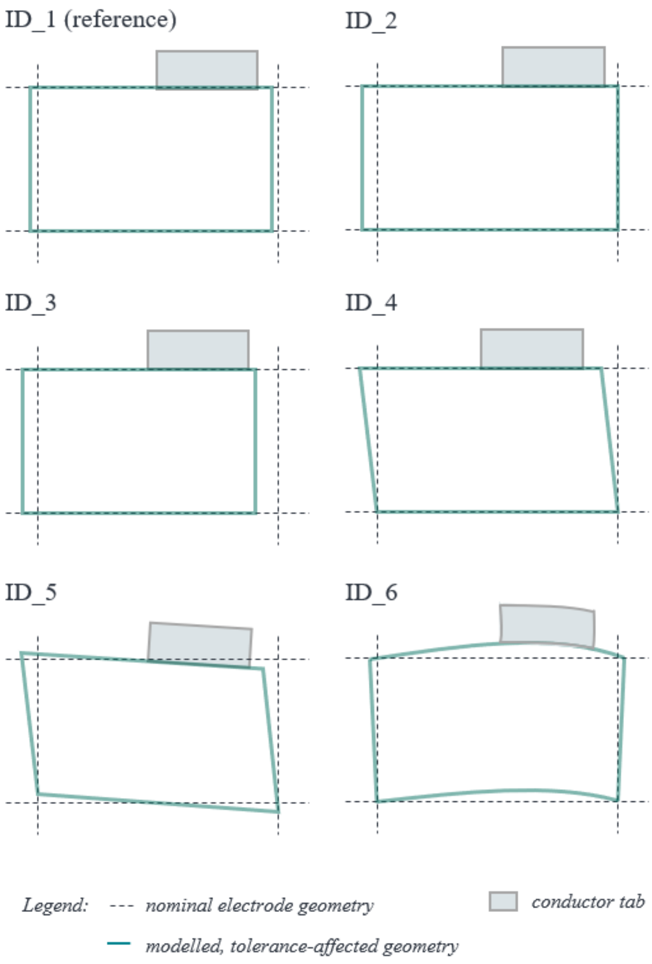

Fig 3. Schematic illustration of the modelled electrodes and their initial position

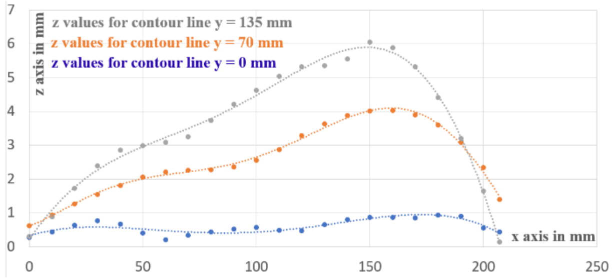

Fig 4. Contour lines of electrode ID_6

Since the dimensions of ID_6 cannot simply be derived from geometric relations, the arc lengths of the three contour lines were measured using Siemens NX. The results are as follows:

- Arc length contour line *y = 0 mm: 208.03 mm*
- Arc length contour line *y = 70 mm: 208.14 mm*
- Arc length contour line *y = 135 mm: 208.53 mm*

It can be seen that the arc lengths differ from each other as expected on the basis of the different amplitudes. However, based on a stacking accuracy of *+/- 0.5 mm*, for example, the arc lengths are still within the tolerance, so that the required tolerance can theoretically be achieved. However, it is not clear how this electrode, as well as the other modelled electrodes, affect the process and the resulting stacking accuracy, which will be investigated in section 3.

3. Results

Within the scope of this paper, all electrodes described in Table 1 were simulated using the model from section 2.2 and the resulting positions of the corner points were examined. The final positions of the corner points are shown in Fig 5.

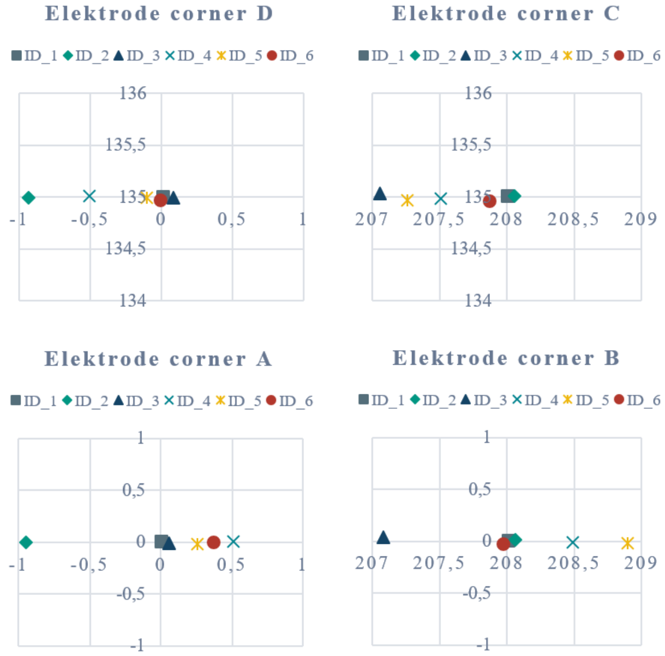

Fig 5. Results of simulation: final position of electrode corners in mm after gripping

Based on the obtained results, the following conclusion can be discussed for the simulated electrode shapes:

- ID_1: As expected, it can be seen that the electrode with nominal dimensions leads to perfect positioning of the electrode on the gripper, which results in perfect stacking accuracy under the assumed boundary conditions. It can be verified that the simulation achieves correct results in principle.
- ID_2: For this electrode shape it can be stated that the electrode is not centred as it could have been assumed in principle. After visual evaluation of the simulation, it can be detected that the conductor tab and its higher stiffness has an influence. If the electrode had a greater stiffness, it would form a perfect arc due to the oversize. However, since the right side of the electrode is stiffer due to the conductor tab, a maximum is asymmetrically formed on the left side of the electrode. When pressed down by the gripper, it leads to an asymmetrical end position of the corners.
- ID_3: It can be seen that the electrode is pushed to the right by the left aligner. Due to the impulse and the friction, the electrode moves a little further in positive x-direction after the mechanical aligner has stopped. This is not a problem as long as the preceding process of electrode separation ensures that the electrode length does not fall below the minimum acceptable length to ensure the required stacking accuracy tolerances.
- ID_4: Here, a displacement of the electrode in x-direction can be determined. A rotation does not occur, as would be expected in principle. This can be explained by the fact that the aligners do not reach to the corners of the table, but stop slightly before it. In addition, the electrodes movement is also blocked in the y-direction. This allows the electrode to be positioned and gripped without rotation.
- ID_5: In this case, significant displacements occur in both the x-direction and the y-direction. Due to the dimensions, the electrode experiences a certain rotation caused by the initial position of the electrode.
- ID_6: It is noticeable that the strong inhomogeneity in z-direction and the associated deviations of the arc lengths from the ideal length lead to displacements in the x- and y-directions. Compared to the other electrodes, the corners no longer lie flat, but take off slightly from the table. This leads to an inaccuracy, since the electrodes and thus also the corners are flattened later in the stacking process.

Depending on the definition of the stacking accuracy value by the stacking machinery operator or their customers, a statement can now be made about tolerable electrode dimensions to meet the stacking process requirements. From this, tolerances can be defined for the preceding processes, in particular to the electrode separation process.

4. Summary and outlook

In this paper, a simulation model was presented which can be used to simulate the stacking accuracy based on electrode shapes with tolerances. It was analyzed that the positioning and gripping processes have a major influence on stacking accuracy. For that reason, the two subprocesses of the stacking process were modeled in particular. The model was then used to simulate six electrode shapes with tolerances.

It could be shown that a tool was developed which helps to better understand and design tolerances for battery cell production. In particular, the separation can be better designed based on the requirements of the stacking process. This makes possible to reduce tolerances and save costs. In addition, an increase in overall battery pack power density is possible as tolerances can be designed in a more targeted manner. Also scrap rate reduction is possible, since parameter values for tolerances can be set faster.

In the future, however, the simulation will have to be validated on a test rig in order to provide more precise information. In addition, further development of the material model appears to be useful. In particular, it should be examined whether the integration of elastic-plastic material behavior is relevant. Once these steps have been taken, large quantities of shapes can be simulated in order to define tolerance windows.

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