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High throughput feeding of battery electrode sheets: Accuracy vs. throughput vs. electrode-damage

Muhammed Aydemir*, Robert Mooy, Alexander Müller, Arne Glodde, Franz Dietrich

Technische Universität Berlin,
Institute for Machine Tools and Factory Management
Chair of Handling and Assembly Technology Research
Pascalstrasse 8-9, 10587 Berlin, Germany

** Corresponding author. E-mail address:* aydemir@tu-berlin.de (M. Aydemir).
https://www.hm.tu-berlin.de/
https://www.linkedin.com/company/tuberlin-hamster

In battery production, excessive throughput maximization of electrode-separator-composite assembly suffers from loss of accuracy and increased damage likelihood. In stacked battery cell designs, this calls for high throughput feeding with high accuracy and low damage. This article analyses robot-based handling, in particular their throughput, feeding accuracy, and damage-free handling. This serves as a comparison reference for the rotary-feeding mechanism, which is analysed afterwards. In this context, scenarios of gripping, stack separation and alignment are introduced and investigated experimentally. These experiments indicate that 160% feeding throughput compared to conventional pick-and-place has been achieved at the same accuracy and without damages.

assembly, productivity, battery-production

1. Introduction and problem statement

Within the production of battery cells for automotive applications, the assembly of the electrode-separator-composite (ESC) is a productivity bottleneck [1]. This implies that the ESC assembly processes account for more than half of the overall battery cell production costs [2]. The challenge in designing the assembly system is to find the most appropriate compromise between throughput and quality, where quality is indicated mainly by accuracy and damages. These challenges motivate the research to improve the throughput significantly while the levels of accuracy, damage and costs need to be preserved.

The approach of this paper is as follows: At first, current ESC assembly technologies are reviewed in terms of throughput, accuracy and damage. This analysis reveals that process intensification by speed up of pick-and-place handling tasks might be limited near the current level. Instead, the subsequent research is directed towards process concepts which avoid the throughput limitation of such pick-and-place handling. A new, continuous feeding mechanism is proposed and characterized in order to show the appropriateness to scale up the throughput considerably.

For automotive applications, battery cell types are commonly of prismatic or pouch shape. The ESC inside these housings can be wound prismatically, so-called jelly-roll, or it can be stacked. Wound ESC consist of continuous electrode materials, whereas stacked ESC consist discrete electrodes [3]. In order to maximize cell energy content, stacked ESC is more and more preferred by battery manufacturers and automakers [2]. This paper hence constrains its scope to high throughput feeding of single electrode sheets for the assembly of stacked ESC.

The ESC assembly procedure is repetitive because a number of time-consuming set and reset movements for handling and stacking the electrodes. Figure 1 illustrates a typical assembly sequence of the ESC, which begins with feeding of discrete electrode sheets from a magazine. Typically, an alignment procedure will follow, to realize the desired placement accuracy.

After placing the electrode on the ESC stack, the handling system has to do a reset movement back to the magazine to pick the next electrode from there. The described pick-and-place operation (PPO) is repeated until the required number of electrodes has been stacked. The fact that the reset movement consumes productive time but does not add value motivates the following approach to search for other processes without such reset movements.

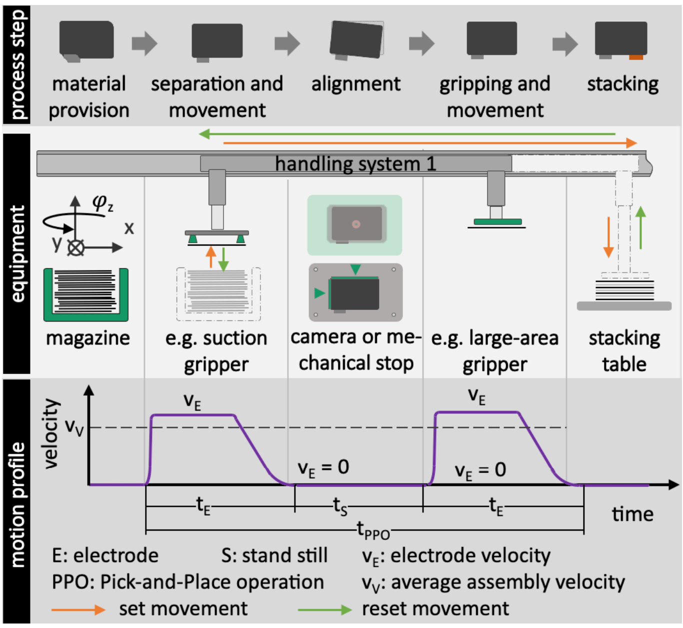


Figure 1: Sequential process of state-of-the-art ESC assembly: process steps, commonly used equipment and motion profile of electrodes.

2. Review of assembly technologies for electrode handling

2.1. Throughput, accuracy and damage

Electrode handling is carried out typically by industrial robots or portal servo systems. The grippers in these systems are often based on the pneumatic principles of vacuum and Bernoulli, and evaluations of these can be found in [4]. Investigations of surface-damage due to gripper wear show that standard or even special vacuum suction cups are usually not suitable to handle the electrodes, which triggered further innovations [5]. This means that, irrespective of the selected principle, each gripping system has to be adapted specifically to the requirements of ESC assembly. The following research is hence particularly interested in damage- and contamination-free grasping, reliable destacking of single electrode sheets and short evacuation times to achieve the desired gripping force.

Industry has formulated the objective to achieve cycle times below <1s for separation, alignment, movement and placement of an electrode on the ESC stack [1]. To understand this objective in relation to the current market situation, the following market review is conducted. In data sheets of ESC assembly equipment, the achievable time for a handling operation of a discrete electrode t_{PPO} is usually stated with respect to fixed dimensions or a range of electrode dimensions. In order to prepare a comparison of these different machines, this information and the battery cell sizes stated in DIN 91252, e.g. BEV1, are used to define example battery performance classes (e.g. 20 Ah, 40 Ah, 50 Ah), which are producible with the considered assembly equipment. Under assumption that the cathode load capacity is 3.5 mAh/cm^2 in all examples, the number of ESC layers inside these battery examples is calculated. This, in turn, is used to compute the throughput of the considered assembly machinery in battery cells per minute. Figure 2 shows this comparison, where the achievable time for a handling operation of a single electrode t_{PPO} and the resulting throughput are indicated. This graph indicates that available machinery is limited through the nature of PPO at around 1 s, irrespectively of electrode dimensions. This finding advocates the use of other processes without PPO to overcome this barrier.

The placement accuracy achieved by available machinery ranges around ±0,1 to ±0,5mm. This is important to note, since, the better the accuracy, the higher the achievable energy density of the ESC and the lower the risk of unwanted and dangerous side reactions induced by inhomogeneous overlap [2]. Common counteractions usually include the deceleration or interruption of the handling movement, in order to increase alignment accuracy. Any substitute process must achieve the same level of accuracy in order to maintain the level of safety.

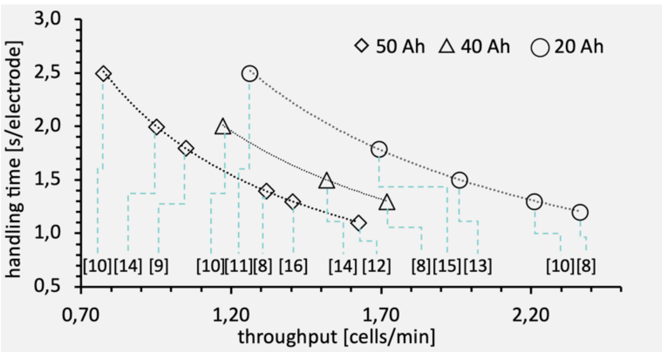


Figure 2: Throughput of current available machinery for ESC assembly. Note, the lower limit of cycle times is currently 1 s per electrode.

2.2. Research activities for high throughput ESC assembly

Related research into throughput improvement has three main approaches: the first is process intensification, where, for example, the reset movement of the handling system is usually parallelized with the set movement of a second handling system for higher throughput. The second approach is to elaborate process integration, for which the cut-and-place module in [6] is an interesting example. The third approach is to increase the level of product integration. For example to laminate electrodes first and then to stack them on top of the ESC. Unfortunately, this increases the amount of undesired non-active material within the battery cell (additional binder and adhesives) [1]. To combine the advantages of these two approaches, continuous ESC assembly process was proposed [7], which lays the basis for the following research.

2.3. Research objective

Industrial ESC stacking solutions rely on pick-and-place handling procedures, where the pausing and reverting of movements limits the throughput. It is hence concluded that further considerable increase of throughput cannot be achieved by process intensification but by substitution, as can be seen in [6] and [7]. However, such substitutes imply completely different process variables, design variables, and interlinked effects, which need thorough understanding to reveal their full capabilities.

The objective of the research reported below is to elaborate and understand the peculiarities of high-throughput feeding and on-the-fly alignment which are based on continuous motion. This is one crucial topic on the roadmap to convert the whole stacking process with intermittent feeding stops into a continuous process. Besides the proposal and characterization of this process, this shall provide understanding about the crucial variables to be considered further and initiate a discussion about the engineering effort for such solutions.

3. Concept of a high throughput feeding mechanism

The following concept elaboration is structured along the handling functions shown in Figure 3.

3.1. Concept requirements

The requirements of highest priority for a continuous feeding mechanism are reliable gripping, quick destacking, narrow position and orientation accuracy, damage-free handling and high throughput.

Separation: The handling characteristics of electrodes are dominated by their limpness (overall thickness <250 µm) and by the stress sensitive surface of the active material. The separation process requires that the electrode must be gripped reliably from the stack, accelerated, released from the gripping device, and fed forward along the desired trajectory. The achievable throughput is limited by the maximum permitted force that must not exceeded during gripping, acceleration and deceleration. The separation process and also all other handling processes within ESC assembly must not deform the electrodes, leave gripping marks or contaminate the surface through detached particles.

Continuous movement: Electrodes are to be moved, aligned, measured and transferred without a significant loss in feeding velocity.

Alignment: The correction of orientation and position according to the designated stacking accuracy determines quality, energy density and cost of the battery cell. In contrast to the reviewed technologies, the correction movement has to occur while the electrode is in motion, in order to avoid loss of material velocity.

DOI: http://dx.doi.org/10.14279/depositonce-12438

3.2. Concept for high throughput feeding and lab demonstrator

The proposed process concept, displayed in Figure 3, contains two sections, namely the "separation and movement" and the "alignment and movement". The columns "material provision" and "joining with separator" illustrate the upstream/downstream interfaces of the two sections considered.

In the "separation and movement" section, a vacuum intake located on a rotating draw-off-roll (DOR) grasps stationary electrodes from a magazine, one at each revolution. This rotational movement transfers the destacked electrode into an accelerated motion and, thereafter, into a belt-drive system. In the subsequent "alignment and movement" section, the electrode is passed through a number of motion stages of counter-rotating rolls. When an electrode passes through these stages, the stages superimpose additional movements in a coordinated manner to align the electrode to the trajectory required at the subsequent's process intake. Such an alignment motion profile is depicted in the lower part of Figure 3. With these superimposed movements, the alignment procedure is continuous and can be realized during constantly high velocities.

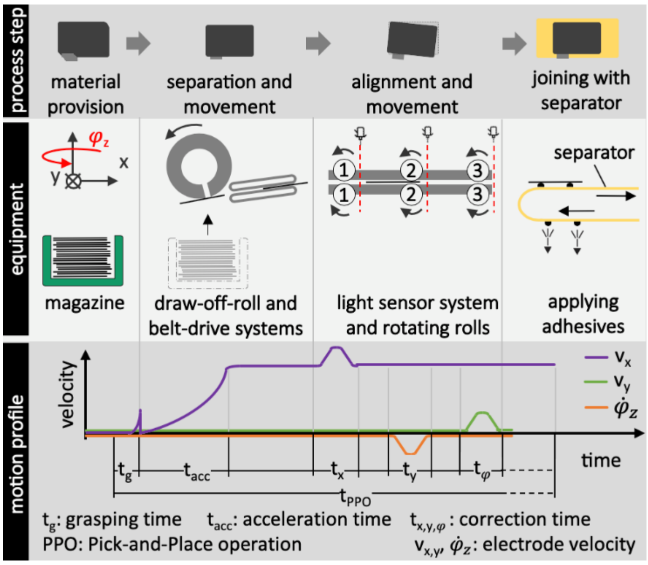


Figure 3: Concept of high throughput feeding mechanism.

The concept has been evaluated by models, simulations and virtual mock-ups, in order to predict the capabilities of this concept. However, there is a variety of uncertainties in practice, which need to be evaluated experimentally to legitimate the proposal. For this purpose, and in order to prepare the integration of this process into a lab demonstrator for the whole battery assembly process, this concept was realized in a physical testbed, see Figure 4.

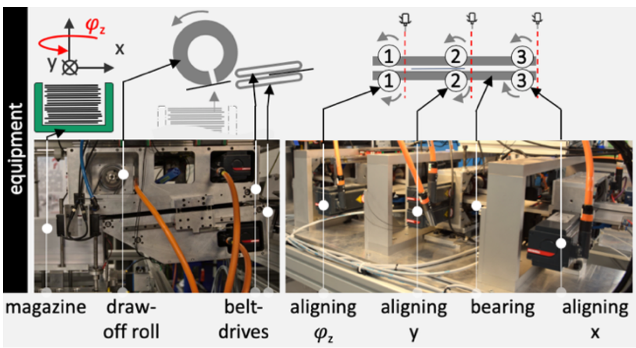


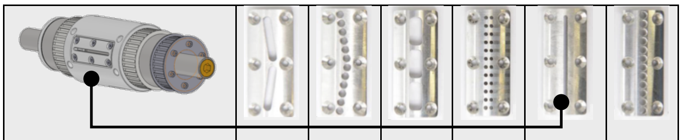
Figure 4: Demonstrator of high throughput feeding mechanism.

4. Experimental performance and sensitivity analysis

The purpose of the following experimentation is to demonstrate the functional performance of the proposed feeding concept and to understand the parameters with most influence on the functional performance. The result consists of recommendations about which subset of design and process variables shall be considered in further research (and which parameters might be of interest in similar applications). The experimentation is organised along the two process sections described above.

In the separation process, screening experiments showed that the success rate depends mainly on the force applied by the draw-off-roll. This is a joint effect of the level of vacuum applied, the shape of the vacuum suction intake, and the friction. Particular attention was put on the intake geometry, because damage caused by overly strong vacuum force was most likely to occur near the edges of the intakes' openings. This significance motivated another set of screening experiments, where variations of the opening geometry of the vacuum intake were tried (at the same level of vacuum). In these experiments, the achieved gripping forces and the damages after 20 repeated grasping tries were recorded. The amount of repetitions was necessary to make the effect visible under the SEM (none of the vacuum intake inserts showed defects after single grasping tries). Table 1 displays the experimental results of the normal force and friction force for a number of these vacuum intake inserts. The absolute amount of damages observed were divided by the normal force observed, in order to obtain a relative index value Q (amount of damages and force were approximately proportional to vacuum level for each vacuum intake).

Table 1: Characteristic properties for different suction inserts



Vacuum intake no.	#1	#2	#3	#4	#5	#6
Normal force [N]	4,9	2,9	8,6	1,8	2,5	2,8
Friction force [N]	3,2	2,1	4,7	1,7	1,1	1,6
Index Q	**0,08**	**0,13**	**0,10**	**0,14**	**0,10**	**0,16**

Preliminary experiments of the separation provide confidence that its output accuracy remains within the intake tolerance of the subsequent alignment. Further, a strong correlation between the velocity and the slip has been detected. The faster the acceleration of the draw-off-roll, the larger the slip during separation with a maximum of 101,46mm at 1320mm/s. The orientation error after separation and acceleration has been measured to be $\Delta\varphi(z)$=0,07°±0,35° and was uncorrelated to the handling velocity. The experiments demonstrate that suction insert no. 4 has a very low impact on the electrode surface, a homogeneous force profile and was able to realize a reliable destacking time of around 67ms, respectively a continuous velocity of 1320mm/s for the downstream process. It was hence selected for further experiments.

4.2. Alignment and movement of electrodes

Figure 5 reports from experiments where electrodes where fed through the alignment rolls and the friction force was measured. It confirms that the roll material and the gap are most significant for damage-free handling and accurate alignment. Besides, the shape of the rolls is significant for the pressure distribution and

DOI: http://dx.doi.org/10.14279/depositonce-12438

unwanted slip-induced damages during alignment corrections. After experiments with different shapes, a spherical roll shape is recommended, because it benefits best from minimized contact.

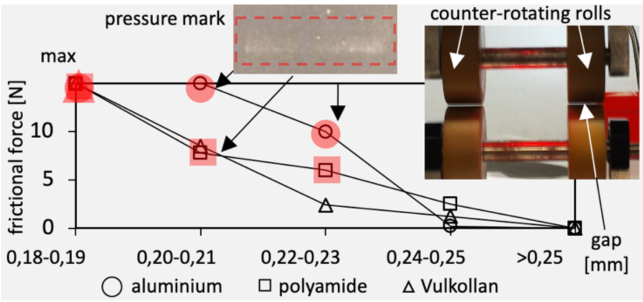


Figure 5: Verifying the capability of damage-free handling electrodes

The alignment of electrodes through a superimposed movement showed a similar trend, because high velocities result in reduced time spans to align *±Δx, ±Δy* and *±Δφ(z)* and increased slip in x- and y-direction and around the z-axis, see Figure 6. The figure represents data from experiments where, for research purposes, remarkably poor intake accuracy of up to *+Δx*=50mm, *+Δy*=7mm and *+Δφ(z)=7°* had to be compensated by the alignment. The electrodes showed no visible damages. An accurate alignment of *+Δφ(z)*=7° was experienced to be too difficult, since the slip is >1°. The experiments have been repeated with *+Δφ(z)*=0.7° showing a slip of >0.002 at 330mm/s and 825mm/s as well as 0.27° at 1320mm/s.

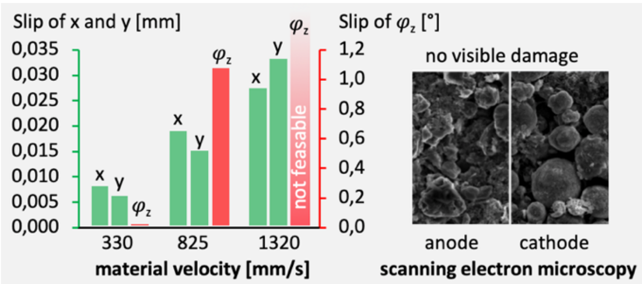


Figure 6: Verifying the efficiency of damage-free aligning electrodes

Summarizing the experimental section, the operational capability of automatically feeding battery electrodes has been documented for velocities from 330mm/s to 1320mm/s, which compares to handling times for a pick-and-place operation of 0.9 to 0.23s/electrode, see Figure 7. Handling accuracy decreases with increasing velocity. Attempts to achieve velocities of 1320mm/s failed so far because the tolerable alignment accuracy was violated. Anyway, an increase of throughput of more than 160% compared to [12] has been demonstrated experimentally, while the individual aligning accuracy and damage-free handling was maintained.

5. Discussion and Conclusion

The review of available technologies stressed that stacked electrode-separator-composites, which are more and more preferred in automotive batteries, will need continuous instead of sequential assembly processes. In this field, feeding and alignment are crucial to establish high throughput processes and need to be understood in detail.

This research has proposed such a feeding and alignment process and realized a lab demonstrator. Experimental significance screening has revealed crucial design and process parameters. Besides, a significant throughput increase has been confirmed experimentally.

This work shows that, with relatively low effort, a significant increase in throughput through a rethink is achievable in this field. This is remarkable because, so far, further improvement efforts through process intensification and optimization have not even been touched. Motivated by this understanding, the concept of process substitution by continuous processes should be extended to other process steps of battery production.

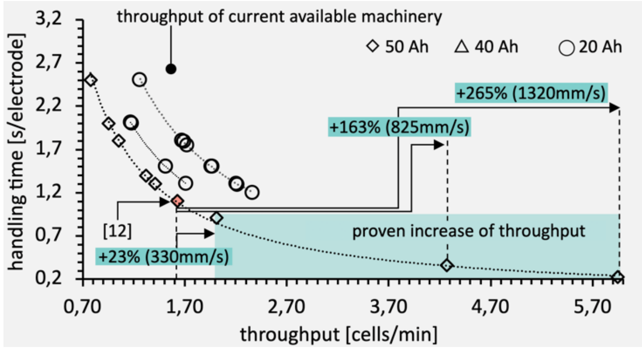


Figure 7: Achieved throughput in comparison to the state of the art.

Besides battery production, the presented process concepts and equipment is capable of separating a variety of further thin-sheet-type materials, such as paper or wafers. The peculiar alignment process, which gains simplicity because it uses light barriers and drive profile timing instead of camera technology, is the foundation for the continuous movement.

Acknowledgement

This research is based on “KontiBAT” No. 03VP01480, funded by the German Federal Ministry of Education and Research.

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DOI: http://dx.doi.org/10.14279/depositonce-12438