Technische Universität Braunschweig

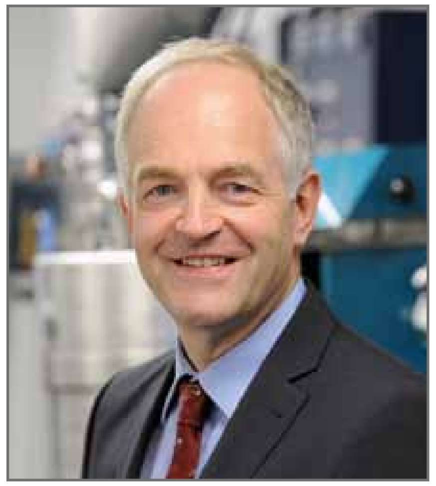
IBPC 2022

INTERNATIONAL BATTERY PRODUCTION CONFERENCE

7 to 9 November 2022

CONFERENCE BROCHURE

WELCOME



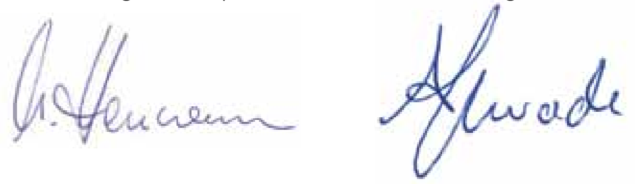
Dear IBPC2022 participants,

Batteries are a key driver of the global mobility revolution and the core of the so-called "Energiewende". The corona pandemic and the Russian war against the Ukraine have shown how important resilient material supply chains are. This is particularly essential for the battery industry. The industry has seen significant progress in production capacities, technological progress in terms of energy capacity and fast charging ability, cost reduction as well as raw material requirements in recent years. An end of the innovation power and capacity increase is not yet in sight. For example, we are experiencing a fast innovation rate regarding new materials, production technologies as well as cell and pack designs that need to be transferred from lab-scale to industrial mass production. In addition, recycling capacities enabling a circular economy need to be further developed in the context of the increasing number of end-of-life batteries (EoL-batteries) as well as post-production scrap. Besides the increasing amount also the diversity of battery materials used are an challenge.

Thrilled with the success of the last four IBPC´s with up to 280 participants and about 50 exciting presentations including six plenarys on recent advancements in battery production, we are delighted to welcome you to the IBPC 2022 as an on-site event in Braunschweig to discuss recent developments and research around battery production and its circular economy. This year's plenary talks, presentations and poster sessions address the innovative electrode production of classical lithium-ion batteries (LIBs) and next-generation batteries, cell design, cell performance and diagnostics, formation and aging, sustainable production, circular economy, the development of recycling processes and battery factory design with associated supply chains. In addition to LIBs with liquid electrolyte, the conference addresses the production of solid-state batteries with two very promising sessions.

We are delighted to welcome speakers and their presentations that deal with the entire battery value chain up to battery recycling and are looking forward to their contribution to the battery production community. We are particularly thankful for the support of our partners, especially VDMA Battery Production and the German competence clusters ProZell, InZePro and greenBatt. A special thank goes to our sponsors Bio-Logic Science Instruments SAS, Bühler AG, Coperion GmbH, Custom Cells GmbH, EIRICH GROUP, Netzsch Feinmahltechnik GmbH, Keysight Technology GmbH, Volkswagen AG and Zeppelin Systems GmbH. Their support enables us to maintain the high quality of the conference. We warmly welcome you and wish you a pleasant stay in Braunschweig with many interesting talks and exciting discussions.

Prof. Dr.-Ing. Christoph Herrmann & Prof. Dr.-Ing. Arno Kwade



BATTERY LABFACTORY

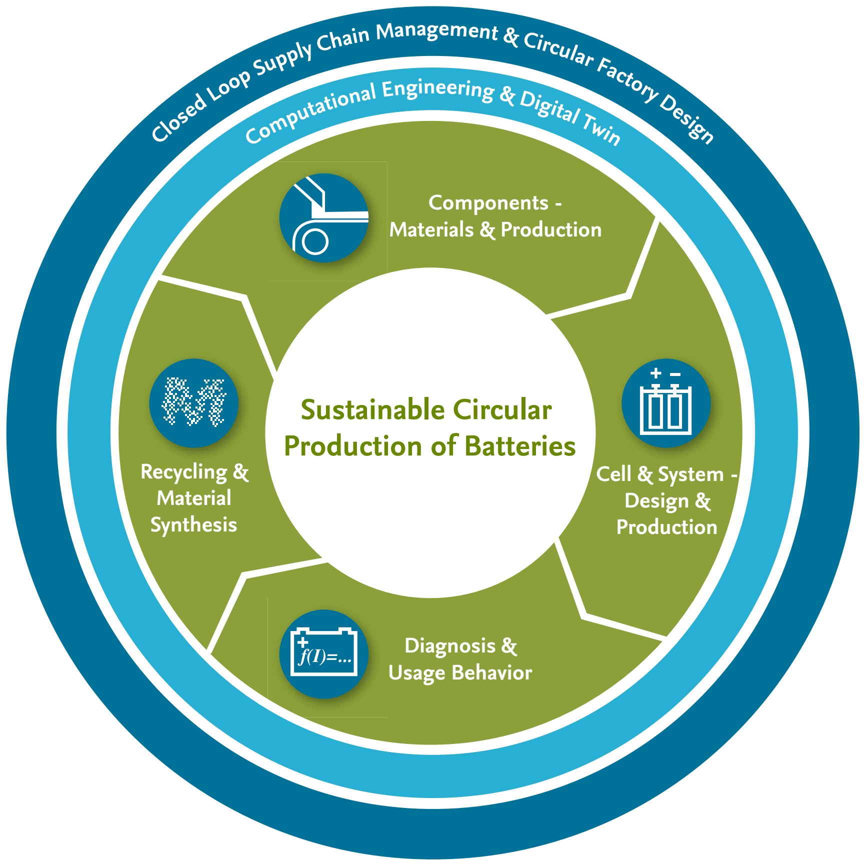
The Battery LabFactory (BLB) stands for an open research infrastructure to investigate and develop electrochemical storage devices from laboratory to pilot plant scale. The research spectrum covers the entire value cycle, from material, electrode and cell manufacturing, up to recycling as well as the subsequent active material resynthesis from recycled raw materials. With this research spectrum, the BLB aims to enable a sustainable circular production of battery cells.

The BLB holds the production infrastructure and characterizing equipment to develop large-sized batteries as well as battery modules and packs. This allows the research on fundamental and application-oriented aspects. The scope of the BLB is to establish a knowledge-driven electrode and cell production to accomplish a fast transfer of R&D into technical or pilot scale production processes. For this purpose, engineers and scientists with different areas of expertise join forces in the transdisciplinary team of the BLB. In detail, 9 institutes of the TU Braunschweig, two from TU Clausthal and one from LU Hannover combine their knowledge and scientific competence. Furthermore, the Fraunhofer Institute for Surface Engineering and Thin Films IST and the Physikalisch-Technische Bundesanstalt Braunschweig (PTB) complete the joined Battery LabFactory Braunschweig.

The BLB represents an open platform for R&D on processes, cell design, diagnostic and simulation of todays and future battery technologies.

BLB BATTERY LABFACTORY BRAUNSCHWEIG

Sustainable Circular Production of Batteries



CONTENT

PARTNERS

BioLogic Science Instruments SAS, with its corporate office in Seyssinet-Pariset, is a French designer and manufacturer who offers powerful laboratory research instruments and software since 1983. The company is characterized by its close relationships with battery development and testing laboratories around the world. With our high precision, high-performance product range of potentiostats, galvanostats, battery cyclers and impedance analyzers we are able to cover a wide field of research: New battery technology, fuel cells, photovoltaics, corrosion, super capacitors, and bio-sensors to name a few. The modularity of our multi-channel potentiostats and our wide range of battery characterization accessories offers highest flexibility to configure the appropriate device according to your needs.

www.biologic.net

Every day, billions of people come into contact with Bühler solutions to cover their basic needs for food and mobility and more. Our technologies are in your smartphone, solar panels, diapers, lipstick, banknotes, the foods you eat, and the vehicles you drive. Bühler offers a wide range of solutions for the crucial process steps in LIB cell production. As a global leader in wet grinding and dispersing technologies, Bühler provides reliable, scalable and industry-proven solutions for wet grinding of active materials and precursors as well as continuous mixing of electrode slurries for lab, pilot and large-scale production.

www.buhlergroup.com

Coperion is the international market and technology leader in compounding systems, feeding technology, bulk materials handling systems and services. Coperion designs, develops, manufactures and maintains systems, machines and components for the plastics, chemicals, pharmaceuticals, food and minerals industries. Coperion has 2,500 employees, nearly 30 sales and service companies worldwide and a total of 30 extrusion systems permanently available for testings.

Your partner for the continuous production of battery materials:
Coperion delivers complete high containment systems for the continuous production of battery masses- from bulk material handling to high accuracy feeding and extrusion.

www.coperion.com

CUSTOMCELLS® - Advanced battery cell development and production

CUSTOMCELLS® is one of the leading companies in the fields of development and series production of special lithium-ion battery cells. Based upon modern process technologies, flexible production environments, access to an extend supply chain and thru a highly experienced R&D team CUSTOMCELLS® develops customer's application driven cell technologies and is handling the industrialization of the developed cell concepts. CUSTOMCELLS® automated series production is one of the most modern battery cell production facilities in Europe. Traceable cell assembly processes, a flexibility in cell chemistry and format, high precision production processes including state-of-the-art quality assurance systems and a unique, modern cell formation and testing makes CUSTOMCELLS® to a leading technology specialist and supplier for the automotive, aerial vehicles, aerospace, medical, oil and gas and for the maritime industry.

www.customcells.org

The EIRICH GROUP is a family-managed group of companies operating in the field of special mechanical engineering with its headquarters in Hardheim, Germany. As one of the world's leading manufacturers of machines and systems for processing raw materials, EIRICH develops, plans and manufactures advanced technologies for mixing, granulating, dispersing, kneading, reacting, tempering and fine grinding since 1863. Solutions for process technology and automation round the portfolio off. A staff of approx. 1,300 employees work at the 15 sales and production sites all over the world.

www.eirich.de

Keysight is the world's leading electronic measurement company, with 13,000 employees in 150 locations worldwide. We offer a full range of formation and test solutions with over 25 years of experience in cell and battery characterization. State-of-the-art software improves production quality, utilization of battery testers, along with inventory tracking. Cloud-based software provides secure access to data from anywhere in the lab.

www.keysight.com

PARTNERS

NETZSCH

The NETZSCH Business Unit Grinding & Dispersing offers an extensive machine program for process engineering, providing solutions for wet and dry grinding, mixing, dispersing and deaeration. Long-term experience, consistent development work, daily contact with our customers and developments with more than 100 patents ensure our technical competence and further attest to our quality-consciousness. The bundling of process-engineering expertise and the extensive machine program, ranging from laboratory to production machines to complete production lines, is unique worldwide.

https://grinding.netzsch.com

The world's changing – and we're changing with it. We're placing the focus on e-mobility, the digital transformation of our brand and smart mobility. But we want to be more than Europe's largest carmaker. We want to deliver the ideas and solutions for resource-friendly mobility and networked traffic systems in big cities and small towns all over the world.

The Volkswagen Passenger Cars brand is present in more than 150 markets throughout the world, produces at over 30 locations in 13 countries and delivered around 4.9 million vehicles in 2021. Around 184,000 people currently work at Volkswagen worldwide. And we want you to be one of them.

www.volkswagen.de

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Zeppelin Systems is a global leader in plant engineering for the handling of high-quality bulk materials. With over 70 years of experience in process engineering and extensive knowledge in handling countless raw materials, Zeppelin Systems offers complete and reliable solutions. With 22 locations worldwide, the company supports its customers from plant design though implementation and provides all after-sales services locally, from a single source. At Zeppelin Systems, innovative processes are just as important as the clever automation solutions and full range of service they provide to cover the entire life cycle of your plant.

Each Zeppelin plant is customized to meet the requirements of each customer be it in the plastic, chemical, battery, rubber and tire, or food industries. With the world's largest technology center network for bulk materials, Zeppelin enables its customers to carry out tests on an industrial scale and verify and optimize their plant design. Zeppelin Systems develops and manufactures its own components for key plant functions, which are also used in third-party plants. For more information, visit www.zeppelin-systems.com.

greenBattNutzung
Querschnittsinitiative Batterielebenszyklus

The BMBF-funded research initiative greenBattNutzung combines the competence clusters Recycling & Green Battery (greenBatt) & Battery Utilization Concepts (BattNutzung). greenBatt aims to develop, design and apply innovative technologies, methods and tools for a sustainable battery life cycle and closed material and resource loops. BattNutzung's mission is to develop, design and apply new concepts for battery system evaluation, linking findings at cell level to the level of battery technology requirements. Both clusters combine a total of 55 research institutes that collaborate in 29 research projects. The initiative is accompanied by an industrial management board ensuring an active exchange between science and industry.

www.greenbatt-cluster.de, www.battnutzung-cluster.de

ProZell
Kompetenzcluster zur Batteriezellproduktion

The aim of the competence cluster is to research and improve the entire process chain of the battery cell production and assess the influence of each individual production step on cell properties, product development costs and sustainability. In cooperation with the BMBF, the KLiB and the ProZell management board, the active ProZell network successfully creates synergies between science and industry. Together, they lay the foundation for a high-performance and cost-effective battery cell "Made in Germany".

www.prozell-cluster.de

VDMA
Batterieproduktion

The VDMA Battery Production department is the partner for all questions relating to machine and plant construction in the field of battery production. The member companies of the department supply machinery, plants, machine components, tools and services for the entire process chain of battery production: From raw material preparation, electrode production and cell assembly to module and packaging production. The current focus of VDMA battery production is on Li-ion technology. We research technology and market information, organize customer events and road shows, hold our own events, such as the annual conference, which has established itself as an important industry meeting place, and are in dialogue with research and science on current topics and on joint industrial research.

https://vdma.org/batterieproduktionsmittel

>extruders >feeders >components >pneumatic conveying >complete systems

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KEYSIGHT

Keysight is the world's leading electronic measurement company, with 13,000 employees in 150 locations worldwide. We transform today's cell and battery measurement experience with innovative technologies for material research, manufacturing, and validation.

Cloud-based software is the key to keeping up with processes and tracking and managing data from anywhere in the lab.

Cell Formation

Keysight solutions scale with cell size, production level, and process complexity. PathWave Cell Formation Manager software tracks formation ensuring quality and consistency.

Cell/Battery Test Lab

PathWave Lab Operations for Battery Test software and Scienlab testers verify cells and battery packs—manage and fully utilize test assets from any location.

KEYSIGHT TECHNOLOGIES

PROGRAMME

CONFERENCE DAY 1 | Nov. 7th

8:30 I Arrival of Attendees

9:00 I Welcome by the Conference Chairs

9:15 I Keynote by Prof. Christoph Herrmann (TU BS/IWF) & Prof. Thomas Spengler (TU BS/AIP)
Towards sustainable battery production systems and supply chains

9:50 I Break

9:55 I **Parallel Sessions**

Material formulation
Room Maschinenhalle I Chair: Dr. S. Zellmer

Tapped density as a quality control for powder in battery manufacturing
Salvatore Pillitteri, Granutools

Optimization of battery microstructures and their electrolyte filling process using pore-scale simulations
Benjamin Kellers, DLR at the Helmholtz Institute Ulm

Dependence of the Electrochemical Performance of LiNi0.5Mn1.5O4 Cathodes on the Conductive Additive for High-Voltage LIB Applications
Heather Cavers, TU Braunschweig/iPAT

Battery Production 4.0 (I)
Room Nimes I Chair: Prof. D. Schröder

Industry 4.0 Software Architecture and Data Collection during Cell Production
Bob Zollo, Keysight

Towards Digital Twin for Sustainable Battery Cell Production: Model-based Digitalization Platform
Gabriela Ventura Silva, TU Braunschweig/IWF

Implementation of Traceability into the Battery Production
Alessandro Sommer, TU Munich/iwb

10:40 I Discussion

10:55 I Break

11:15 I **Parallel Sessions**

Slurry production
Room Maschinenhalle I Chair: Prof. A. Kwade

Continuous processing of negative electrode pastes for lithium ion batteries
Kristina Borzutzki, Fraunhofer FFB

From lab scale to production scale- upscaling of the continuous mixing process for LIB electrode slurries
Valentin Dolder & Desiree Griessl, Bühler AG & BMW

Process development for continuous extrusion coating of battery electrodes and scale up to pilot scale
Jann Seeba, Fraunhofer IKTS

Battery Production 4.0 (II)
Room Nimes I Chair: Prof. C. Herrmann

DigiBattPro 4.0- Development and validation of digitalization artifacts in real-life production scenarios
Florian Maier, Fraunhofer IPA

Flexible production of humidity-sensitive electrodes for future battery cells
Christina Hein, CustomCells

Automated data management and process parameter determination in R&D cell production
Markus Hagen, Batalyse GmbH + Fraunhofer ICT

12:00 I Discussion

12:15 I Lunch Break

13:15 I Planery Discussion by Dr. Stephan Witt (Jagenberg AG) & Hans Schneider (Zeppelin Systems GmbH)
Machinery and plant engineering supply for European battery Gigafactories

13:55 I Keynote by Dr. Christoph Weber (ACC- Automotive Cells Company)
On the way to accelerate mobility for all

14:30 I Break

14:45 I **Parallel Sessions**

Microstructural effects during processing
Room Maschinenhalle I Chair: Dr. M. Kandula

Stressing of SBR during dispersion and its micro-structural effect on slurry and electrode properties
René Jagau, TU Braunschweig/iPAT

Structure and rheology of electrode slurries and their importance in battery manufacture
Carl Reynolds, University of Birmingham

Bridging battery performance ageing and electrode calendering parameters through model-based estimation of tortuosity
Clara Ganuza, Cidetech Bilbao

Battery supply chains and factory designs
Room Nimes I Chair: Prof. T. Spengler

The Role of Digitalization in the Battery Supply Chain
Philipp Wunderlich, Accenture GmbH

Resilient production planning in closed-loop supply chains for lithium-ion batteries
Christian Scheller, TU Braunschweig/AIP

A flexible and extensible process model for battery production systems with value chain interface capabilities for LCA analysis
Daniel Perez Clos, NTNU

15:30 I Discussion

15:45 I Postersession

17:15 I **Parallel Sessions**

Development of recycling processes
Room Maschinenhalle I Chair: Prof. B. Yagmurlu

Recovery of lithium from process water of Li-ion battery recycling processes
Aliza Marie Salces, Helmholtz Institute Freiberg for Resource Technology

Controlled Lithium enrichment in artificial minerals in LIB derived slags based on thermodynamic tools and concentration by froth flotation- an update to the state of research
Hao Qiu, TU Clausthal/IFAD

Direct reuse of Al and Cu current collectors from spent lithium-ion batteries
Emma Kendrick, University of Birmingham

Electrode, cell and module diagnostics during production
Room Nimes I Chair: Prof. C. Schilde

Inline Characterization of Electrode Properties and Associated Challenges in the Calendering Process of Lithium-Ion Battery Electrodes
Andreas Mayr, TU Munich/iwb

Investigation of defect formation in lithium-Ion battery anode and cathode manufacturing for improved in-line quality assurance
Arnaud du Baret de Limé & Artur Scheibe, Fraunhofer IKTS & RWTH Aachen/PEM

Inline intermediate product characterization and quality control for lithium ion electrode production
Alexander Schoo, TU Braunschweig/iPAT

18:00 I Discussion

18:15 I Break

PROGRAMME

18:30 I Industrial Solutions for Cell Production

Room Nimes I Chair: Prof. A. Kwade

Gigafactories equipped with Eirich MixSolver® and ContiFeeder® technology- a field report
Stefan Gerl, Maschinenfabrik Gustav Eirich GmbH & Co KG

Potentials for Yield Enhancement By Inline Metrology for Slurries and Coatings
Marcus Klein, Suragus GmbH

Improved optical inline particle inspection
Jochen Sander, Dr. Schenk GmbH

Reducing costs of cell cycling during high volume production to monitor the output quality of a Gigafactory
Albert Gröbmeyer, Keysight

BioLogic – Key Parameters for Advanced Techniques and Analysis in Battery Cycling
Sandra Kienast and Julia Berlin, BioLogic

High Accuracy Feeding: A key to continuous mixing process
Keith Melton, Coperion K-Tron (Switzerland) LLC

NETZSCH efficient dispersion systems for Li-ion and ASSB Battery Electrode coatings
Alberto Masi, NETZSCH-Feinmahltechnik GmbH

19:40 I End of Day one, start of evening event

PROGRAMME

CONFERENCE DAY 2 | Nov. 8th

8:30 I Keynote by Ingo Höllein (Federal Ministry of Education and Research (BMBF))

9:05 I Keynote by Frank Blome (PowerCo SE)
Series Production of Cell Factories in Europe

9:40 I Break

10:00 I **Parallel Sessions**

Circular economy and sustainability
Room Maschinenhalle I Chair: Prof. C. Herrmann

Sodium-Ion Batteries- Advancing in sustainabilty?
Jens Peters, University of Alcalá

Carbon Footprint of Production Equipment – Implications for Cell and Equipment Suppliers
Joscha Schnell, P3 automotive

LCA of Recent Innovations in the Battery Cell Production using a Modular Material and Energy Flow Model
Nicolas von Drachenfels, TU Braunschweig/BLB

Production of solid state batteries
Room Nimes I Chair: Dr. P. Michalowski

Upscaling of solvent-free synthesis of sulfide-based solid electrolytes and demonstration of a continuous production process
Michael Grube, Fraunhofer IST

Tailoring solid electrolyte and composite electrodes for large scale production of solid-state batteries
Fatima Nadia Ajjan, Austrian Institute of Technology GmbH

Characterization of production-relevant properties of all-solid-state battery materials
Timon Scharmann, TU Braunschweig/IWF

10:45 I Discussion

11:00 I Postersession

12:30 I Lunch Break

13:30 I **Parallel Sessions**

Electrode processing
Room Maschinenhalle I Chair: Dr. S. Zellmer

Enabling High Loadings for Aqueous NMC811 Cathodes via Multi-Layer Coating
Lukas Neidhart, Austrian Institute of Technology GmbH

Dry battery electrode production by IWS DRYtraec® technology
Benjamin Schumm, Fraunhofer IWS

A time-resolved investigation of the vacuum post-drying for lithium-ion-battery electrodes
Thilo Heckmann, KIT/TFT

Boundary areas in next-generation batteries
Room Nimes I Chair: Dr. P. Michalowski

Ion Transport Investigations on Hierarchically Structured Cathodes with Nano Porous Particles for Sodium-Ion Batteries
Luca Schneider, KIT/IAM

Rational optimization of cathode/electrolyte bilayer assemblies for all-solid-state batteries
Artur Tron, Austrian Institute of Technology GmbH

Influence of the cathode mixing parameters on the coulombic efficiency loss of LFP solid-state polymer electrolyte batteries
Maria Carmen Morant-Miñana, Cidetech Bilbao

14:15 I Discussion

14:30 I Awarding of the poster prizes

14:45 I Keynote by Tom Einar Jensen (FREYR Battery)

15:20 I **Parallel Sessions**

Electrode drying
Room Maschinenhalle
Chair: Prof. K. Dilger

BearLITE- processing- now proven, enables new battery manufacturing
Kai K. O. Bär, adphos

Scaling effects of fast laser drying processes in battery production
Samuel Fink, Fraunhofer ILT

Application of the conductive drying process for the electrode production of lithium-ion batteries
Tobias Krüger, TU Braunschweig/ifs

Formation and aging
Room Nimes
Chair: Dr.-Ing. S. Essmann

Investigation of thickness changes of multilayer lithium-ion battery cells during cycling
Niklas Penningh, TU Braunschweig/iPAT

Fast Charging Capability during the Formation of Coin and Pouch Cells
Robin Drees, TU Braunschweig/elenia

Detailed Model-based Lithium-Ion Cell Diagnosis after Fast Formation
Daniel Witt, KIT/IAM

16:05 I Discussion

16:20 I (Virtual) Tour BLB – Room Maschinenhalle or BLB

16:45 I End of Conference

PRESENTATION ABSTRACTS

Battery Production 4.0

Implementation of Traceability into the Battery Production

Alessandro Sommer
Technical University of Munich, Institute for Machine Tools and Industrial Management

One of the key challenges of battery cell manufacturing is to reduce production costs. Production defects and manufacturing inaccuracies, combined with high value streams, cause cost-intensive scrap costs. To reduce these, conventional batch tracing is not sufficient since the quality-critical intermediate products are not considered in a differentiated manner. In order to ensure consistently high quality, data-based methods and applications are increasingly used in the literature. The aim is to uncover unknown relationships or interdependencies in the manufacturing chain, based on collected production and quality data. Additionally defective intermediate products should not be processed further, but should be diverted from the process chain at an early stage. This requires production-specific and consistent data in order to exploit the full potential. The combination of continuous and discrete manufacturing processes of the electrode production and the cell assembly often results in the inconsistency of production data sets. To address this deficiency, tracking and tracing approaches in battery cell production are increasingly referenced in the literature. However, no experimental evidence for the functionality of a traceability approach for scrap reduction has been provided so far.

In other areas of industry, e.g. markings such as barcodes or RFID chips applied by inkjet printing are used for conventional tracking of products. Such an integrated segmentation of the production processes can improve data quality, but no reference to battery cell production has been made so far. The presentation shows a concept as well as the integration of a traceability concept of product and process data with a resolution down to the level of individual electrode sheets. For this purpose, a suitable data management for continuous and discrete data sets in an automated processing manner is also presented.

Industry 4.0 Software Architecture and Data Collection during Cell Production

Bob Zollo
Keysight Technologies, R&D Department

This presentation covers software for formation, aging, and grading of small-scale production lines for R&D or cell prototyping. Attempts to build such a line from individual cell testers or from a scaled-down manufacturing system suffer from compromises. A tuned solution for formation lines can be based on Industry 4.0 technologies, thus providing a system with flexibility and agility that securely manages processes, data collection, and storage. This data is an important battery intelligence data source to track cell provenance and history as from cell development through manufacturing and eventually into batteries deployed in the field. For companies who are building new R&D / prototype cell manufacturing, this presentation will identify what options are available based on modern software technologies and will highlight the important characteristics to consider before deciding on the kind of system software they need to deploy for cell prototyping. With this knowledge, these companies can make informed investment choices to achieve flexibility needed for research while having the control and management of a full sized manufacturing line.

DigiBattPro 4.0 - Development and validation of digitalization artifacts in real-life production scenarios

Florian Maier
Fraunhofer Institute for Manufacturing Engineering and Automation IPA

The project Digitalized Battery Production 4.0 (DigiBattPro 4.0), funded by BMBF, focuses on enhancements in cell manufacturing through digitalized artifacts. Its consortium consists of VARTA Microbatteries, VARTA Consumer Battery, Fraunhofer IPA, and ZSW Baden-Württemberg. The three main goals are (1) to make digitalization visible, (2) to identify the benefits of digitalization in battery manufacturing, and (3) to ensure adaptability to other factory environments. This project's unique characteristics are built up by the commitment to validate the newly developed digital artifacts in real-life cell-manufacturing environments. Therefore, the digitalized artifacts are jointly developed by the research and industrial partners and together tested and validated in the manufacturing environment of VARTA. This is achieved by utilizing up to 200 complete 8-hour-shifts to run extensive experiments and validation scenarios.

To address the right artifacts for digitalization, the working groups are developing and re-evaluating use cases every six months and presenting them in front of a decision-making body (which consists of the process- and digitalization experts). These use cases must address a pre-defined list of criteria (e.g., scientific impact, expected improvements of KPIs, TRL, etc.).

This presentation highlights three of those use cases mentioned above. (1) Traceability: Implementation of a closed traceability chain, starting from slurry mixing and coating, until testing each completely assembled battery cell. This is crucial information for further data analysis, process optimizations, and second-life or recycling purposes. (2) End-of-Line-Testing (EoL): The reliability of EoL quality checks has a high impact on the Cost-of-poor-quality (COPQ). This use case will increase the sensitivity and the specificity of testing methods based on automated optical measurements combined with artificial intelligence, mainly to reduce fault negatives. (3) Digitalization infrastructure: New digital artifacts need an environment to be deployed and executed. On-demand computing power and storage concepts for a huge amount of data with fast read-times are needed. This third use case focuses on an easy-to-use and easy-to-integrate digitalization infrastructure to enable power users and system architects to implement their digital automation scenarios.

Towards Digital Twin for Sustainable Battery Cell Production: Model-based Digitalization Platform

Gabriela Ventura Silva
TU Braunschweig | Institute of Machine Tools and Production Technology (IWF)

The application of batteries in electric vehicles and stationary energy storage systems is widely seen as a promising enabler for sustainable mobility and for the energy sector. Given the urgency to meet climate targets, recent studies forecast a 10- to 15-fold growth in European demand for lithium-ion batteries between the years 2020 and 2030. A sustainable future for lithium-ion battery cell production and the mobility sector depends, therefore, on an economically and environmentally efficient production as well as high-performance batteries. However, battery cells are manufactured in a process chain with highly specialized, energy-intensive, and strictly interlinked processes. As a consequence, each process is defined by various specific parameter interactions which lead to a manifold of cause-effect relations on a product, process, and production level. In order to fully understand these interdependencies and move away from expensive trial-and-error operations of production lines, a methodology is needed to provide knowledge-based decision support and improve the battery cell quality and production performance. This work presents a digitalization platform to quantitatively assess the parameter interdependencies along with the battery cell production based on the coupling of process-oriented, production-oriented, and battery cell models. Moreover, the platform provides a digital representation of the electrode and cell production, allowing, for example, the definition of optimal production settings. The framework is implemented in a browser-based interface that enables an easy configuration of the processes and process chain to be simulated as well as result visualization. The digitalization platform can be implemented as part of a cyber-physical production system to provide decision support and ultimately control of the production line, thus increasing the efficiency of the entire battery cell production process.

Automated data management and process parameter determination in R&D cell production

Markus Hagen
Batalyse GmbH and Fraunhofer Institute for Chemical Technology ICT

The production of lithium-ion batteries is characterized by comparably high scrap rates. With material costs of 70-80% of the cell price, scrap is a significant cost factor. By using AI, correlations of process data and cell properties can be determined, and particularly quality-relevant process steps can be identified.
However, the prerequisite for the use of AI is a clean collection, description and tagging of data which is very time-consuming and demanding for R&D.
In the BMBF-funded InZePro projects "KontElPro", for solvent-free electrode production and "AgiloBat2", for the agile production of format-flexible cells, the "Batalyse" software suite is extended to solve this problem.
The "Batalyse" software suite is capable of automatically collecting, categorizing, linking, and evaluating test, analysis, and production data.
Quality-relevant parameters of the produced (lab) cells such as capacity, resistance and power can thus be directly correlated with process parameters and data. The complete process chain of input materials, (intermediate) products, sensors, equipment, process parameters and all evaluated result data of the produced cells is stored in the database.
In the project "AgiloBat" one main goal is also to speed up the cell design and production planning process rapidly. The task of the software is to read-in the target parameters of the to be produced battery modules and cells and to translate them to process parameters in a specific workflow.
The workflow integrates process owners/experts of every specific battery production process and will also take historic production campaign data into account.
All data, correlations and logic are provided by this database via an interface making it an ideal choice to forward structured training data for AI applications.
In the talk we present the work of Batalyse GmbH focusing on automated test data evaluation and the progress of Fraunhofer ICT within the projects "KontElPro" and "AgiloBat".

Flexible production of humidity-sensitive electrodes for future battery cells

Christina Hein
CUSTOMCELLS®

As the use of lithium-ion batteries expands, so do the requirements for new battery cells. New technologies are needed to meet the various demands, such as high energy densities or high charge and discharge currents. The focus of the development is on the battery cell components, espe-cially the electrodes as they determine the key performance of the cells. The production of cells with the future lithium-ion chemistry is determined by the process technology used in addition to the ambient conditions. Nickel-rich materials are increasingly used on the cath-ode side, while Si compounds are often planned for the anode in conjunction with pre-lithiation. The processing of these materials results in special demands on the production environment due to their high-water sensitivity.
Cell development is influenced by various aspects beside sustainability and supply chain. A major influence is the modern development environment. In this presentation, a flexible process chain for the processing of all common lithium-ion battery materials as well as for new material developments will be presented. A suitable, flexible, decentralized develop-ment environment from slurry production to cell finishing will be presented as well as spot-lights on specific influencing factors.

Battery supply chains and factory designs

Resilient production planning in closed-loop supply chains for lithium-ion batteries

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The increasing demand for electric vehicles leads to continuing rapid growth of lithium-ion battery production. To reduce resulting environmental and social impacts and to counteract the potential supply bottlenecks, original equipment manufacturers integrate recovery processes into their supply chains, e.g., recycling and repurposing. This results in closed-loop supply chains for lithium-ion batteries, which are characterized by global structures, a multitude of actors, and an inhomogeneous distribution of bargaining power.
Additionally to the extensive challenges of the global closed-loop supply chains, further challenges occur in unforeseen disruptions. The Covid 19 pandemic and the Ukraine war are clear examples that have impacted original equipment manufacturers' and suppliers' capacities as well as material and component prices significantly. These crises occur abruptly and with significant consequences for the entire supply chain. For example, nickel shortages and high prices are leading to production downtime and rising production costs in battery production. While the development of potential resilience capabilities is possible, these are often in conflict with efficiency goals. Therefore, such capabilities should only be deployed to a certain level. In this context, two approaches are needed.
On the one hand, approaches for the supply chain design should consider resilience aspects. On the other hand, approaches for the production planning need to integrate the implemented capabilities and enable a quick rescheduling of the production plans in the occurrence of a crisis. While several approaches enable the design of resilient supply chains, adequate approaches for resilient production planning are missing.
Therefore, we develop and apply a mathematical optimization model for resilient closed-loop production planning to enable a quick response to crises and analyze the different capabilities of resilient supply chains. The model is applied to a comprehensive case study based on existing closed-loop supply chains of lithium-ion batteries in Europe to analyze the effectiveness of various resilience capabilities depending on different effects of crises.

A flexible and extensible process model for battery production systems with value chain interface capabilities for LCA analysis

Daniel Perez Clos
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The rapid increase of battery production factories around the world to meet the ambitious projected battery demand within the global economies green shift, poses great challenges for the industry in terms of battery types and production method choices. Being able to assess which production routes, factory design and machinery are most suitable for an efficient and environmentally friendly process, are key factors in enabling successful project executions and future plants scale-up. The maturity of lithium-ion batteries has given this technology a head start in the current factory production boom, which is already causing significant price increase in raw materials and can potentially lead to supply chain bottlenecks. Alternative battery types and chemistries might thus emerge to balance the battery demand with the resources' availability and ease of extraction, refining and recyclability.
From an environmental perspective, it is paramount to develop LCA tools that can assess the global impact of the different available and future technologies in a comparable manner, which can help both industries and governments to make key decisions to adapt to a complex and rapidly shifting reality.
In the present work a battery production model has been developed in python with a modular architecture that enables a flexible model extension to consider and compare different types of battery chemistries, geometries, production methods and production routes. In addition, a flexible stream and process modularity has been implemented with interface capabilities with

value chain models, that can be used to perform LCA studies that consider upstream and downstream processes, from mineral extraction to battery recycling. A general description of the model and a few comparative case scenarios will be presented with focus on outlining the challenges in terms of value chain data availability that is commonly present in this type of studies.

The Role of Digitalization in the Battery Supply Chain

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Accenture GmbH

Lithium-ion battery technology has reached maturity through extensive research over the last decades and is about to reach significant economic scale thanks to the transformation of the automotive industry. Europe is now preparing its industry for a rapidly growing demand in sustainable battery storage. The last months have shown that the numerous projects for large-scale cell production plants are accompanied by announcements for the creation of local supply chains. Next to the established Asian players, the emerging local market comprises powerful automotive OEMs, who still undergo the digital transformation themselves, but also agile startups who think “digital first”. The race is on and the next years will show who will succeed in setting up Gigafactories and conquer market shares in the mobility, energy and industrial sectors.

In this presentation, we share cross-industry perspectives and insights from Europe’s new battery market to critically assess the role of digitalization in this domain. Are digital technologies a chance to catch up on leading cell manufacturers or will it only play a minor role in an unpredictable market that is driven by global raw material supply dynamics and constant technological evolution?

We will present case studies of state-of-the-art solutions that are being implemented in the battery value chain and especially in cell production plant designs. Technologies like digital twins, machine learning and AI applied in Gigafactories aim to make the battery production more efficient, cheaper and sustainable. Production scrap minimization, reasonable process automation and material traceability and play crucial roles for the quality of the battery cells produced. Digital enterprise and plant architectures (SCADA, MES, ERP) can facilitate easier production scaling while the blueprints must offer enough flexibility to deal with short product development cycles and steadily improving manufacturing processes.

The big challenge is that battery cell manufacturing is a unique multidisciplinary process that leads to a highly complex electrochemical device – proper battery data management not only plays a role in production, but it is necessary to optimize the entire battery lifecycle, which starts with the mining of the rae materials. Further downstream in the value chain, battery users and recyclers are already adopting digital technologies such as battery passports of software platform for battery management, not only to comply with future EU directives and thrive for a circular battery economy, but to strengthen their position in the market.

Boundary areas in next-generation batteries

Rational optimization of cathode/electrolyte bilayer assemblies for all-solid-state batteries

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Solid electrolytes with high ionic conductivity of >10−3 S cm−1 have become commercially available and new materials are continuously developed. The race for higher ionic conductivities has become less important and the focus of solid-state-battery research shifts more and more to the interface between active material and electrolyte particles. Electro-chemomechanical aspects for the fabrication of all-solid-state batteries need to be considered to develop scalable production technologies.

In this work, investigations on wet-chemical processing of cathode/electrolyte bilayers using Li6PS5Cl as electrolyte and NMC811 as active material are presented. First, key parameters for the fabrication of electrolyte and composite cathode layers are identified and optimized with special focus on the influence of binder materials and their interaction with selected solvents. Furthermore, experimental considerations regarding the combination of electrolyte and cathode layers to form bilayer assemblies are discussed and strategies to avoid cross-contamination and improve the cathode-electrolyte interface are presented.

Ion Transport Investigations on Hierarchically Structured Cathodes with Nano Porous Particles for Sodium-Ion Batteries

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An important property for the application of a cell is rate capability, which can be improved by reducing the ionic resistance of the electrode. Ionic resistance can be separated into ion transport within the electrolyte phase in the pore structure and solid diffusion in the active material. Since solid diffusion is much slower than electrolyte diffusion, a promising approach to reduce ionic resistance is the application of active materials with an electrolyte accessible internal porosity. This approach is investigated for sodium-ion batteries (SIBs), which offer some advantages over lithium-ion batteries (LIBs) such as cost per kWh and the use of abundant materials. Therefore, SIBs for energy storage will come more and more into the focus in the coming years. Sodium vanadium phosphate (NVP) was investigated as nano porous cathode materials for SIBs. It was synthesized by the agglomeration of nanoparticles to larger secondary particles with defined internal porosity. This nano porous material is known from LIBs to have diffusion-related advantages compared to bulk particles. [1] The larger specific surface area and shorter diffusion paths inside the active material enhance the rate capability, and the small primary particle size prevents the particles from cracking and leads to improved cycling stability. [2] However, the branched pore structure of the intragranular pores also leads to higher tortuosity with reduced effective electrolyte conductivity. [3] An open question is the individual contribution of the intra- and intergranular pores to the ion transport. To answer this, the impedance of electrodes with nano porous NVP particles was measured in symmetrical cells with blocking conditions. An advanced transmission line model (TLM) is used to separate the ionic resistance in intra- and intergranular pores. To get a deeper insight into the electrodes, different particle diameters and their influence in multilayer configurations are also investigated and discussed. By this, the talk provides a practical understanding of ion transport in hierarchically structured electrodes with nano porous particles.

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Influence of the cathode mixing parameters on the coulombic efficiency loss of LFP solid-state polymer electrolyte batteries

Maria Carmen Morant-Miñana
CIC energiGUNE

Lithium solid-state batteries are commonly presented as an alternative to liquid electrolyte systems due to the absence of volatile components and higher achievable energy densities. Among them, polymer electrolyte batteries, consisting of a composite cathode, metallic Li anode and a polymer electrolyte, have the advantage of achieving close contact between the cathode active material (AM) and the electrolyte, mitigating crack formation, and improving ion-transfer between the AM and the catholyte due to the soft nature of the polymers. However, the cathode-electrolyte interfaces are heavily influenced by the processing parameters of the cathode since they affect the structure of the electrode by changing the distribution and size of the cathode active material, the conductive additive and the catholyte. In PEO-based catholytes, these variations are mainly related with the viscosity and, consequently, molecular weight of the polymer, which must be adjusted to obtain composite electrodes with optimal electrode architectures and minimal interface resistances. Therefore, this work will describe the effect of the dry and wet mixing parameters of the PEO-based composite cathodes on the delay of the coulombic efficiency loss onset throughout their cyclability.

Circular economy and sustainability

Sodium-Ion Batteries - Advancing in sustainabilty?

Jens Peters

University of Alcalá

Sodium-ion batteries (SIB) are among the most promising alternatives to common lithium-ion batteries (LIB). Their supposed environmental friendliness and avoidance of scarce and often critical raw materials (especially lithium) is repeatedly cited as an important argument for their further promotion and development. However, the knowledge base in this regard is still weak and relatively little is known about the actual environmental impacts of different types of SIBs compared to current LIBs and under consideration of their full life cycle.

Based on a recently published study, this presentation will discuss the potential advantages and disadvantages of different SIB types, addressing the different cell chemistries currently available on the market and their specific recyclability. It presents a simple tool specially developed for this purpose for detailed modelling of the individual composition of LIB and SIB cells and the quantification of the energy and material inputs for their manufacturing and recycling. These can then readily be introduced into common life cycle assessment software for comparing the environmental performance of the different SIB cells with that of current LIBs.

It turns out that SIBs can achieve similar good or even better results than common LIBs in many areas. However, the used cathode materials and the achievable energy density are a more important factor than the shuttling ion (lithium or sodium). In particular, SIBs that are free of nickel and cobalt and at the same time achieve sufficient energy densities show very favourable results. When the recycling phase is considered, the disadvantage of cell chemistries containing cobalt and nickel is partially offset, with correspondingly larger credits obtained from the recovery of these materials. As a consequence, current LIBs still have a slight advantage in terms of greenhouse gas emissions (mainly due to their higher energy density), while SIBs score well in terms of resource demand. However, LIBs are particularly dependent on effective recycling processes, while SIBs can achieve favourable results even with lower recycling rates. Overall, most SIBs show a very promising environmental performance, provided that ecodesign aspects are consistently pursued in their further development.

Carbon Footprint of Production Equipment – Implications for Cell and Equipment Suppliers

Joscha Schnell

P3 automotive GmbH

Lithium-ion batteries are a key for a transmission towards cleaner energy and transportation. Alongside with new legislation (e.g. European battery regulation) and sustainability requirements from automotive OEMs, a holistic view of the lithium-ion battery supply chain and the associated carbon footprint will be required. Up to now, mainly the cell materials and energy consumption during production have been taken into account when considering the carbon footprint of a battery cell. However, the announced worldwide ramp-up of production capacities will also require a huge amount of machinery and equipment for the production of lithium-ion cells. So far, the carbon footprint of the machines in the production process has been neglected. How big is the carbon footprint of all the machines in the production process of a cell? Within this presentation, we will give insights on our calculations and the implications this has for cell manufacturers and equipment suppliers.

LCA of Recent Innovations in the Battery Cell Production using a Modular Material and Energy Flow Model

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TU Braunschweig | Battery LabFactory Braunschweig (BLB)

Battery cells and their production processes are developing continuously towards higher efficiency. Conventional Life Cycle Inventories (LCI) applied in Life Cycle Assessment (LCA) studies are either numerical or parametrized, which inhibits the application to changing premises from battery development. Therefore, we developed an approach to develop modular material and energy flow models (MEF) for the battery cell production, which builds on modularized, reusable process modules. The modular MEF model is connected to the Brightway2 framework to generate LCI for the five different scenarios: 1) extrusion based slurry preparation, 2) water based electrode production, 3) dry coating, 4) thick electrodes and 5) change of active material. We will present LCA results for each of the scenarios and compare them to the baseline. The case study results shows that the modeled upcoming battery production process and material innovations, particularly the dry coating process, can contribute to a reduction of more than 15 % in carbon dioxide equivalent emissions and even more in other impact categories. With the presented approach, it is possible to model process and product innovations in a common environment, which enables a comparative analysis under changing model premises. This implies the development of reusable models at process level, which can be flexibly adapted and combined to different process chains. This reduces the effort to evaluate process variations significantly and contributes to the use of LCA as an engineering tool.

Development of recycling processes

Recovery of lithium from process water of Li-ion battery recycling processes

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In Europe, an era of battery recycling is shaping new industries as spent lithium-ion batteries (LIBs) are considered, in addition to mining, as a potential source of battery raw materials with high prospect of environmental and economic incentives. Several recycling routes are being proposed combining hydrometallurgy and pyrometallurgy techniques and with emphasis on the mechanical pre-treatment (i.e., sorting, shredding, sieving) to pre-concentrate the LIBs component into a coarse metal fraction (Fe/plastics, Al, and Cu rich) and a fine electrode powder fraction (graphite and cathode active material- CAM). During LIB recycling, particularly in wet operations, specific LIB components such as Li and F easily dissolve into the water which results to material losses. For instance, immersion of an INR18650 battery in 1L water yielded a 100 mg/L Li and 140 mg/L F concentration. Moreover, the implementation of thermal treatment to liberate the electrode powder from the metal foils causes a carbothermic reduction of CAMs creating a more soluble Li compound which can be recovered by water leaching. Recently, froth flotation of pyrolyzed black mass aiming to separate graphite and CAM revealed a rather high concentration of Li in process water of 1,000 mg/L representing a 45% Li dissolution. A concentration of 2,600 mg/L Li was also reached during water recirculation in the flotation experiment. Hence, this work aims at the recovery of lithium from process water of battery recycling processes through the ion-exchange processes. Using commercial IX resins, the preliminary result shows a recovery of ~80% Li from flotation process water can be achieved after 15-min contact time. Precipitation experiments were also performed which produced a ~94-99% purity Li2CO3 powder.

Controlled Lithium enrichment in artificial minerals in LIB derived slags based on thermodynamic tools and concentration by froth flotation - an update to the state of research

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The pyrometallurgical recycling route is essential for recovering valuable metals from spent lithium-ion batteries (LIBs) due to its large processing capacity and ability to handle a broad range of input materials [1]. Besides the recovery of metals such as cobalt and nickel, the effective recovery of lithium from the by-product- lithium-bearing slags- has become a critical issue in improving the pyrometallurgical route to achieve comprehensive recycling.

Froth flotation, a high efficient mineral separation technology, is applied to specifically composed and comminuted slags. The presentation will give an update on the state of research in the greenBatt project “PyroLith”. It aims at separating the lithium-rich mineral phase from the slag, thus effectively minimizing feed material volume in the subsequent hydrometallurgical process for lithium recovery and improving recovery efficiency.

In order to reveal and even predict the complex interrelationships between initial composition and phase content of the slag, CALPHAD (Calculation of Phase Diagram) [2] for lithium containing systems [1] in combination with a new thermodynamic database considering manganese in a certain composition field is applied to specifically design composition and solidification routes to generate target lithium-rich mineral phases suitable for flotation, while achieving the first stage of lithium enrichment in the slag. The floatability of the lithium-bearing minerals and gangue phases then have been investigated. After that, the effects of metal ions on floatability were studied. This investigation is an integral part of developing the slag flotation reagent regime, which is key to achieving lithium enrichment in the pyrometallurgical recycling route of spent LIBs.

“PyroLith” research project is as part of the umbrella concept greenBatt of the German Ministry of Education and Research for battery research.

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Direct reuse of Al and Cu current collectors from spent lithium-ion batteries

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The ever-increasing number of spent (Lithium-ion batteries) LIBs has presented a serious waste-management challenge. Current collectors which are normally Al and Cu foils, are important components in LIBs and take up more than 15% of the weight of LIBs. Direct reuse of current collectors can not only effectively reduce LIB waste but also avoid long recycling processes and bring economic and environmental benefits. However, there is a lack of work reported on the direct reuse of current collectors in the literature. Here, we successfully directly reuse Al and Cu current collectors reclaimed from commercial spent LIBs. The reused Al and Cu under different treatments differ markedly in surface morphology and exhibit distinct wettability, adhesion and electrical conductivity. Both reused Al and Cu current collectors show similar performance as the pristine current collectors, except for the reused Al current collector which delivers lower capacities than the pristine Al at high C rates. This work provides substantial evidence that the direct reuse of Al and Cu current collectors is possible and also highlights the importance of the surface morphology of current collectors on LIB performance.

Electrode drying

BearLITE - processing - now proven, enables new battery manufacturing

Kai K. O. Bär

adphos Innovative Technologies GmbH

BearLITE (Battery electrode advanced rapid Light Initiated Thermal Emission) allows acceleration of present available, electrode coatings whether solvent or water-based potential anode as well as cathode recipes.

The typical todays limits of increased drying rates, due to otherwise occurring cracking and/or binder migration caused damages, as multiple reported for convection driers, IR – and even laser-based electrode coating drying processes, are not observed with BearLITE.

The partially even enhanced resulting battery cell performance with the BearLITE-processing has been multiple proven now for a wide range of potential electrode coatings, as will be presented in this paper.

In addition, the herewith possible optimized electrode-coatings processing, like enormous reduced necessary drying time, energy requirements, operation costs and new process configurations and even 3D-multilayer productions are outlined.

Scaling effects of fast laser drying processes in battery production

Samuel Fink

Fraunhofer Institute for Laser Technology ILT

The increasing demand for energy storage devices like lithium-ion batteries (LIB) requires fast and energy efficient processing technologies. One important step in battery production is the drying of anode slurries. To make this process more energy efficient and less space consuming laser-based drying can be utilized to process water-based anode slurries in a continuous process. The approach of using high intensity laser radiation to quickly dry anode slurries has already been investigated but never been transferred to a continuous coating and drying process. For this purpose, a laser drying module has been developed and set up in a continuous coating machine at Fraunhofer ILT to allow drying experiments at coating speeds of up to 10 m/min. In this presentation the interaction between laser radiation with the components in the slurry is presented. As high heating rates and evaporation rates of water of up to 1 g/s can be achieved, damage to slurry components like CMC and SBR needs to be carefully avoided. Processing parameters like drying temperature, coating speed and film thickness are varied and their effect on the anode is investigated. As high evaporation rates might lead to binder migration, the adhesion of the anode on the current collector foil is quantified. The results indicate that fast drying with laser radiation can be implemented under the correct boundary conditions.

Application of the conductive drying process for the electrode production of lithium-ion batteries

Tobias Krüger

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To match the steadily increasing demand of lithium-ion batteries all battery production steps have to be enhanced in terms of quality and performance. In this regard, the drying process of electrodes holds great potential for improvement. The main challenge of state-of-the-art convective drying methods is the high energy consumption within the drying step.

This study focuses on the development and prototypical implementation of a new method for drying electrodes based on conduction heating. By applying an electric current to the current collector, the metallic foil is immediately heated due to its electrical resistance according to Joule’s law. Since the heat is generated within the metallic material of the current collector, the conductive heating process allows for the efficient drying of the coating starting from the interface between the coating and the current collector. This in turn, could lead to a significant reduction of heating time and energy losses compared to conventional convective drying methods, respectively.

However, the negative impact of high drying rates on electrode properties is well known as a reduction in cycle stability due to binder and carbon black segregation may occur. As a result, the drying rate of conventional convective drying processes is limited. This may also be the case, when the novel conduction-based heating method is applied.
Within this study, conductive drying experiments were carried out on SMG-A5 anodes as well as NMC-622 cathodes on a laboratory scale at different drying intensities and drying times. The heat distribution of the coating was observed using an infrared camera to characterize the temporal development of the drying process. In addition, the drying rates and total power consumption were determined. Finally, the conductive dried electrodes were further examined to investigate the influence of the drying process on their electrical and mechanical properties as well as on their electrochemical performance. Based on the results, the transferability of the already know impact of the convection heating process on the electrical and mechanical properties of the electrodes to the conductive heating process is evaluated.

Electrode processing

Dry battery electrode production by IWS DRYtraec® technology

Benjamin Schumm
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Today's battery electrode production uses a slurry coating process for the deposition of the active layer on thin metal foils. In order to realize a high throughput, the deposited wet film has to be dried in a up to 100 meters long drying section where the solvent is removed from the wet layer. This process step leads to high space and energy consumption. As a consequence, solvent-free dry coating processes are increasingly getting into the focus of cell manufacturers and material suppliers.
With the DRYtraec® process Fraunhofer IWS has developed an alternative and green production technology for battery electrodes. In DRYtraec®, the dry mixture consisting of active material, conductive carbon black and PTFE binder is introduced into the gap between two counter-rotating calender rollers. The shear force in the calender gap leads to the formation of so-called PTFE fibrils. As a result of the process control, a dry film forms on the faster rotating roller. This dry film is subsequently transferred to the current-collector foil. The carrier roller or the current-collector take over the mechanical stabilization of the dry film. This represents a decisive advantage for realizing a high process speed and good scalability.
Here, we present the dry coating of LFP electrodes with DRYtraec®. Process-relevant parameters are discussed and their influences on the film formation are explained. Moreover, the dry coating technology platform at IWS with a TRL-6 process chain for continuous electrode coating (max.10 m/min double sided coating on 20 cm width) as well as pouch cell testing is presented. Process-limiting factors are discussed.
Besides LFP, many further active materials can be processed, as well. However, one major advantage of the technology is also its compatibility with next-generation battery materials, such as sulfide-based solid electrolytes. This makes DRYtraec® to an efficient and versatile coating technology for a greener large-scale battery electrode production.

Enabling High Loadings for Aqueous NMC811 Cathodes via Multi-Layer Coating

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A straight-forward way of maximizing the energy density of Li-ion batteries is to increase the thickness of assembled electrodes. Unfortunately, establishing thick coatings with homogenously distributed material components and sufficient mechanical stability brings an extra level of complexity to the manufacturing process. Especially drying parameters must be selected carefully to minimize binder migration within the coating. High concentrations of binder material at the top of the electrode can have blocking effects on Li-ion transport pathways and additionally cause delamination of the layer from the substrate foil.
Performing multiple coatings on top of each other has proven beneficial for thick electrode fabrication: The evolution of major defects can be suppressed, and further processing is facilitated due to an increase of adhesion to the current collector foil. Additionally, multi-layer coating creates numerous possibilities to establish 3D-like architectures within the electrode for example by introducing material gradients. We recently demonstrated that cells with multi-layered cathodes outperform conventionally manufactured cells at rate capability tests. Also, the adhesion strength of the coating was improved by 40%, following the multi-layering method.
In this work, Ni-rich lithium nickel manganese cobalt oxide (NMC811) was used as active material to produce multi-layered electrodes. Binder concentrations in the top layer were reduced in multiple steps. Investigations on mechanical integrity and electrochemical performance were conducted for water-processed cathodes of high areal loading (> 8 mAhcm-2) at full cell level. Decreasing the amount of binder showed beneficial results during rate capability test and long-term cycling. An increase of up to 40% in specific discharge capacity was achieved compared to conventionally prepared electrodes at 1C.

A time-resolved investigation of the vacuum post-drying for lithium-ion-battery electrodes

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For competitive battery cells, an important prerequisite is energy savings in the cell production. An essential cost factor in the manufacturing process of Li-ion batteries poses a subsequent post-drying process. In this process, moisture adsorbed from the air gets removed from the compounds of the battery by a high energy input. Otherwise, the adsorbed moisture reacts with the electrolyte in the operation of the battery, leading to its degeneration. Literature has revealed a connection between electrochemical performance and the remaining moisture content. In order to remove the moisture cost efficiently from the compounds of the battery, this process step needs to be understood completely. Therefore, a precise and comprehensive simulation along with knowledge of the sorption equilibrium of water and the kinetics of mass transfer reveals optimization potential of energy consumption and process acceleration.
This work investigates the water mass transport in porous electrodes during the vacuum post-drying experimentally and theoretically. The time-resolved vacuum-drying curves are measured with a modified setup of a magnetic suspension balance at variable temperatures and pressures. Furthermore, as physicochemical basis for transport phenomena, sorption equilibria of the compounds of a Li-ion battery have been ascertained and provide the basis for the interpretation of the drying curves. This study focuses on the influence of the binder system and temperature on the vacuum post-drying process, which is investigated on samples in an industrially related coil geometry.
This work contributes to the research performed at CELEST (Center for Electrochemical Energy Storage Ulm Karlsruhe) and Material Research Center for Energy Systems (MZE). The authors would like to acknowledge financial support of the Federal ministry of Education and Research (BMBF) via the ProZell cluster-project "Epic" (Grant number: 03XP0295A).

Electrode, cell and module diagnostics during production

Inline Characterization of Electrode Properties and Associated Challenges in the Calendering Process of Lithium-Ion Battery Electrodes

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Electrodes are a multi-component and multi-material system comprising a complex particle matrix coated on a metallic substrate foil. Calendering represents an essential and property-determining process in the manufacturing of lithium-ion battery electrodes as it significantly affects the mechanical and electrochemical properties. During the calendering process, the coating is compacted in a roll-to-roll process to achieve the aimed porosity, which leads to complex interactions at the particle level. To achieve an increase in capacity and volumetric energy density of lithium-ion battery cells, electrode processing is moving towards increasingly higher compaction rates. This leads to an increased occurrence of defect patterns during calendering, which have a negative impact on the further processability or are classified as scrap. A cost-efficient production of high-quality elec-

trodes is therefore becoming a focus of current research. As an interface between electrode manufacturing and cell assembly, the calendering process facilitates the early detection of rejects by integrating inline characterization and quality assessment of electrode properties.
This approach utilizes different measurement techniques (e. g., laser triangulation and confocal measurement) for inline characterization of electrode properties. Product characteristics of electrodes, such as coating thickness or defect patterns in form of corrugations, are addressed and potential inline characterization methods of these characteristics are discussed. The experimental results show that by integrating inline measurement techniques, product features such as coating thickness and defect patterns can be detected and quantified using process metrics for quality assessment. In this context, the challenges associated with the integration of measurement technology and data processing when applied in battery production are considered. Additionally, theoretical scaling effects in the transfer from pilot to industrial scale are illustrated.

Investigation of defect formation in lithium-Ion battery anode and cathode manufacturing for improved in-line quality assurance

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Missing quantitative thresholds to separate acceptable product deviations from actual defects represent a major challenge in today's production of lithium-ion battery cells. Tied to the fear of potentially hazardous battery failures, this lack of product and process knowledge makes proper in-line quality assurance one of the most challenging tasks throughout the manufacturing process.
To address this issue, three key processes in the preparation of NMC 6-2-2 cathodes and graphite anodes were investigated in detail: i) the mixing of raw materials, ii) the coating of the electrode slurry and iii) the subsequent drying of wet coated electrode foils. Combining theoretical fundamentals and experimental practice, critical process parameters leading to defect emergence were hereby identified. Furthermore, additional insights regarding parameter combinations that increase the likelihood of defect formation were gathered and used in a following step to determine a window of stable processing conditions.
All defects were generated using research pilot line infrastructure and roll-to-roll coating equipment. Defects themselves were classified depending on their type, size, shape and frequency of occurrence as well as optically measured by a high-definition line-scan camera. Selected samples were further characterised using chromatic confocal and scanning electron microscopy techniques. Finally, full cells were built using a selection of electrodes exhibiting significant defects to evaluate the corresponding electrochemical performance in terms of capacity retention and achievable C-rates.
This research is part of the KritBatt-Project within the AQuA-Cluster and was made possible by funding from the Federal Ministry of Education and Research (BMBF).

Inline intermediate product characterization and quality control for lithium ion electrode production

Alexander Schoo
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The process chain in battery cell production consists of several intermediate products, each produced in one or more consecutive process steps. Every process step requires associated peripherals and complex technical building equipment to realize defined environmental conditions and allow the processes to comply with high quality standards necessary for well-performing battery cells. Despite the high requirements of individual process steps, there is a wide variety of interacting influencing parameters between consecutive process steps as well. The implementation of innovative inline measurement methods enables improved and automated process monitoring and thus cost reduction through performance optimization and scrap minimization. Furthermore, continuous data acquisition allows the application of statistical methods for the definition of process tolerances in a given process window. This data can further be used to correlate the data with corresponding offline methods and therefore qualify intermediate products in real time. Especially in the context of smart manufacturing, continuous process monitoring is key for data-driven applications and the implementation of cyber-physical systems in battery cell production.
This presentation will pay special attention towards the continuous drying of lithium-ion battery electrodes and highlight the usage of inline color and area weight sensors. On the one hand, the color sensor can be used to determine the carbon black segregation and indirectly predict the adhesion of the graphite anode. On the other hand, the basis weight sensor can be used to describe the capability of the roll-to-roll coating process and to adjust the balancing of the electrodes to the process variations using the six sigma theory in order to reduce the scrap rate.

Formation and aging

Detailed Model-based Lithium-Ion Cell Diagnosis after Fast Formation

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The first cycling of a lithium-ion battery is a crucial process step in battery production. Although this so-called cell formation comprises only few cycles, it impacts both the long-term degradation as well as the performance characteristics of the final cell. Common formation times are on the order of multiple days due to relatively low C-rates, presenting a unique opportunity for meaningful cost savings.
For a knowledge-based process optimization, a sound understanding of the interrelation between cell formation and performance-limiting cell properties is essential. As a result, detailed cell diagnostics including the characterization of the formed solid electrolyte interphase (SEI) are indispensable. Here, the preparative effort for most experimental methods for SEI characterization like SEM or XPS is significant and will also require cell disassembly. In contrast, physicochemical modeling allows for a recurrent cell diagnosis based on non-destructive electrochemical measurements. To enable a holistic cell diagnosis, we extended the classic Doyle-Fuller-Newman battery model with a detailed modeling of the SEI. This allows to describe C-Rate and EIS data with the same parameter set, providing detailed insights into performance-limiting processes and their evolution along cell aging.
For a deeper understanding of the impact of cell formation on individual cell properties, we performed a broad experimental study at different temperatures with different formation currents, using small-scale three-electrode test cells. Our results show that the final cell performance depends strongly on the chosen formation conditions. With the model-based cell diagnosis, we found that the bulk and interfacial SEI properties are not the major reason behind the differences in the fast charge/discharge capability of the cells. Instead, the effective transport properties in the anode electrolyte phase are driving the performance differences. This highlights that proper cell formation is not only about a stable SEI but also about minimizing the impact of SEI growth on transport in the bulk electrolyte phase.

Investigation of thickness changes of multilayer lithium-ion battery cells during cycling

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Due to their high energy density, Lithium-ion batteries (LIBs) have conquered important shares of the rechargeable battery market, particularly for electric vehicles (EVs) and plug-in hybrid electric vehicles (PHEVs). However, a LIB cell undergoes thickness changes during cycling, and it can be distinguished into a reversible and an irreversible share. The reversible share is called breathing and occurs during one charge-discharge cycle. It is mainly caused by the volume change that the electrode active material undergoes during (de)intercalation of the lithium ions. The irreversible share is called the swelling phenomenon which denotes the permanent thickness or pressure growth due to the cell ageing. The main reasons could be additional layer growth, or solid electrolyte interface (SEI) formation and gas evolution [1,5].
In particular, negative electrode active materials exhibit strong volume changes which will cause mechanical degradation within the cell. Effects can be the pulverization of the electrode layer, delamination of the active material leading to electrical discon-

nection from the current collector or even SEI damage [1,4,5]. Depending on the rigidity of the housing or the stack stress of a battery cell, also inactive components like the separator can be affected [2,3]. Therefore, it is important to investigate how compression will act on the cell's performance and cycle life, possibly preventing some of the previously mentioned effects. Transferred onto a battery pack in an automotive application, this information is crucial when it comes to pack design, even more, when a module-free approach is considered and numerous cells are mechanically connected in series. Inside the pack, cells are braced for various reasons – optimizing of the volumetric energy density, ensuring operating functionality and safety by not having any loose parts inside the pack and, in the end, affecting the performance and cycle life of the cells. Pressure or thickness change measurements can furthermore give deeper insights into the electrochemical cell behaviour during cycling [7-10].
In this work, a test bench is developed to characterize the breathing behaviour of commercial LIB cells. By using the pouch format, it can be ensured to obtain an almost direct mechanical feedback. A uniaxial spring-braced approach is chosen to let the active material expand and contract between two metallic plates during just moderate pressure variations to keep the inner cell layers in permanent contact. After applying pressure onto the cell, a relaxation and retardation period is inserted to ensure pressure homogeneity, and allow for the settling of the plates since some of the inactive cell components exhibit viscoelastic material behaviour. Cycling behaviour and thickness change are monitored during a variation of different parameters (bracing pressure, C-rate) in order to investigate the magnitude of the breathing phenomenon both to identify the influencing factors and the effect of the bracing measure. Additionally, tests beyond the cell's operating limits will be carried out to obtain further information about the mechanical behaviour of the cell.
First results show that a variation of the charging rates leads to differences in thickness change of a mildly braced cell. In this particular case, both reversible and irreversible dilation shares are present.
Hereby gained insights will serve battery electric vehicle manufacturers that are aiming to optimize their battery pack regarding operating efficiency, sustainability and mechanical safety. Another important aspect for the cell manufacturer is the scalability of the breathing phenomenon. By elaborating this information, it will be possible to determine the breathing behaviour in correlation with the cell thickness (number of compartments) for a specific active material combination.

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Fast Charging Capability during the Formation of Coin and Pouch Cells

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The formation of lithium-ion batteries is one of the most time-consuming processes during the production. Common formation methods consist of several relatively slow constant charging and discharging cycles as it is believed to guarantee good performance of the Solid Electrolyte Interphase (SEI) on the negative electrode. The SEI has a significant impact on the performance, aging and safety of battery cells. Aiming at faster production times, cheaper production costs and better properties of lithium-ion batteries, the optimization of common formation methods is necessary.

This contribution is focused on developing optimized fast charging formation procedures for high-energy NMC622/G pouch cells. Therefore, different parameters of influence as current density, temperature, external pressure and the degassing timing is varied. By means of an equivalent circuit model, the resistance during the formation is calculated which shows significant differences when varying the different parameters of influence. Based on measurements with three-electrode coin cells the maximum fast charging capability during the formation is determined by controlling the maximum current close to low positive potentials of the negative electrode in order to avoid lithium-plating. This fast charging strategy is applied to multi-layer pouch cells. Based on optical post-mortem analysis it is shown that lithium-plating can be successfully prevented during the optimized fast charging formation. In contrast, state of the art constant-current-constant-voltage fast charging methods lead to significant lithium-plating. Furthermore, the optimized formation procedure result to similar cell properties compared to slow formation procedures

Industrial Solutions for Cell Production

Reducing costs of cell cycling during high volume production to monitor the output quality of a Gigafactory

Albert Gröbmeyer
Keysight Technologies

The quality of cell production is measured for every cell as it passes through many quality gates during the manufacturing process. However, a key parameter, the cell's cycle life, cannot be measured on every cell because this will take too long, and the measurement destroys the cell by cycling it to its end of life. The only practical way to measure cycle life is on a sample basis. In a Gigafactory, the high production volume of cells means even a sample basis will require many cells to be cycled, creating practical problems around capital investment and and operational costs (energy) to run this long-term quality check, which can take weeks or months to test each cell. In this case study, we will show a novel approach used by a major cell maker to implement a cell cycling quality gate in their Gigafactory. This novel approach will be compared against a more traditional method. Factors such as of the amount of capital equipment needed, floor space, safety, energy consumption, and data analysis will be considered. Lastly, future possibilities to create an even more efficient and cost-effective approach will be explored.

NETZSCH efficient dispersion systems for Li-ion and ASSB Battery Electrode coatings

Alberto Masi
NETZSCH-Feinmahltechnik GmbH

The market for Lithium-Ion-Batteries (LIB) and next generation All Solid State Batteries (ASSB) is rapidly growing and evolving. Therefore, cell producers demand scalable cost efficient processes.
Planetary mixers are mature and often used as state-of-the-art. Due to limited mixer sizes, multiple planetary mixing systems are required to meet the slurry demand in large factories.
Especially LIB Gigafactories require alternative processes in order to reduce production time and cost of the cells.
The new NETZSCH system separates the individual mixing and dispersion steps within the slurry production. Raw materials are treat selectively and with adjusted energy input. The modular concept enables cell producers to react flexible on material variations, single steps of the process and allows optimizing consequently the process time. Each process step is fully controllable.
Next generation of batteries (ASSB) needs specific new processes for synthesis of high performing solid electrolytes as well as small production lines for first sampling going in automotive validation process.

Improved optical inline particle inspection

Jochen Sander
Dr. Schenk GmbH

Dr. Schenk GmbH has developed a significantly improved optical particle inspection for Lithium Battery coated anode and cathode foils. This is achieved by a special illumination technology in combination with an improved analysis method. A post processing AI based classification further increases the accuracy.
The talk will review basics of particle control, explain the basic challenges of inline detection of very small particles (10µm) on coatings with microstructures of the same dimensions, and present the results of Dr. Schenk's new solution approach.
The outlook shows additional cost saving possibilities, which goes along with a combination of this technology with coating control or geometry measurement.

High Accuracy Feeding: A key to continuous mixing process

Keith Melton
Coperion K-Tron (Switzerland) LLC

Coperion delivers complete high containment systems for the continuous production of battery masses: from bulk material handling to high accuracy feeding and extrusion.
The production of the battery mixtures, dry or slurry, requires the precise combination of active, conductive, binder and other ingredients.
There is a strong trend towards continuous processing using extrusion, with many added efficiencies over traditional batch processing, however there are increased challenges as a result. In this presentations we highlight these challenges and solutions for the feeding equipment, including material characteristics, such as toxicity, principles of operation, mechanical solutions, measurement through weighing and control approach, concluding with a definition for high accurate feeding.

Potentials for Yield Enhancement By Inline Metrology for Slurries and Coatings

Marcus Klein
SURAGUS GmbH

Electrodes and separators are major cost drivers in battery cell manufacturing industry. Due to high-throughput and low cost-of-ownership requirements, uptime and ultimately productivity of manufacturing equipment needs to be increased for printing, wet coating, and vacuum deposition processes. Constant high yields and yield enhancement is crucial for line operators. The knowledge where and why yield is lost is the basis for yield improvement. Inline monitoring is enabling such analysis. This talk addresses potentials to monitor inline processes and derive actions to improve yield by non-contact high frequency impedance spectroscopy. This monitoring technology is able to ensure coating quality and process stability for both the incumbent as well as emerging high-volume manufacturing processes.
Eddy current impedance spectroscopy derives information of electrical and dielectric characteristics by analyzing the material response to electro magnetic fields. Metrics such as sheet resistance, thickness, drying status and areal capacity can be assessed. Due to its high sensitivity to conductivity, permeability, and permittivity, high-frequency eddy current technology registers a signal shift from a recipe variation of active materials (e.g. LiCoO), solvent contents, and graphite materials. In light of the current demands in slurry, electrode and extrudate characterization, high-frequency eddy current technology is well suited to researchers' and process experts' needs alike. HF electromagnetic eddy current sensors can be implemented in mapping instruments for complete surface characterization and also integrated into pilot lines and high-volume manufacturing settings. This talks provides an overview of process steps, monitoring options also shows example results across several battery manufacturing concepts.

BioLogic – Key Parameters for Advanced Techniques and Analysis in Battery Cycling

Sandra Kienast and Julia Berlin
Bio-Logic Science Instruments GmbH

Bio-Logic Science Instruments SAS, with its corporate office in Seyssinet-Pariset, is a French designer and manufacturer who offers powerful laboratory research instruments and software since 1983. The company is characterized by its close relationships with research and testing laboratories around the world. With our high precision, high-performance product range of potentiostats, galvanostats, battery cyclers and impedance analyzers we are able to cover a wide field of research: New battery technologies, fuel cells, photovoltaics, corrosion, super capacitors, and bio-sensors to name a few. The modularity of our multi-channel potentiostats and our wide range of battery characterization accessories offers highest flexibility to configure the appropriate device according to your needs.
This presentation focuses on key parameters that need to be considered when looking beyond the classical cycling curves recorded in battery performance testing with a battery cycler. We will review the different working modes and the operational quality factors for these different modes so you can properly use your testing equipment to perform advanced tests like: differential capacity analysis (DCA) and high precision coulometry (HPC) or electrochemical impedance spectroscopy (EIS) and receive valid results.".

Gigafactories equipped with Eirich MixSolver® and ContiFeeder® technology - a field report

Stefan Gerl
Maschinenfabrik Gustav Eirich GmbH & Co. KG

The Eirich mixer has impressively proven its exceptional performance for the production of electrode raw materials and mixtures for lithium/sodium ion batteries and Supercaps in the last 10 years and has found its way into more and more R&D laboratories, pilot productions and also Gigafactories all over the world. In the production of coating slurries, as a MixSolver® it reduces the process time from hours to minutes compared to the mixing systems usually used and, with its extraordinary flexibility in terms of the processability of the raw materials but also the range of setting parameters for optimising the electrode properties, it outperforms all other mixing systems available on the market. The cells produced with MixSolver®s show at least equal, but often also enhanced electrochemical cell properties.
The Eirich mixer is the heart of a more or less complex plant technology consisting of powder handling, liquid dosing up to slurry transfer to the downstream coaters. To ensure the high throughput requirements of the Gigafactories and a continuous supply to the coater, Eirich has developed the ContiFeeder® process, which delivers monitored and qualified slurries to the coater by means of the QualiMaster® LIB QM concepts. A Gigafactory with almost 5 GWh capacity using these technologies has been successfully commissioned in Asia.
From the first batch onwards, the 1:1 scale-up of the recipe and mixing sequence developed by the customer worked without any problems and coating slurry with excellent properties was delivered to the coater. Through targeted adaptation or variation of the operating parameters, the energy consumption in the MixSolver® could be optimised from an initial 13 Wh/kg to only 7.7 Wh/kg, without any influence on slurry properties. This made it possible to prepare the slurry completely without using the double jacket cooling. The high dosing accuracy of the Eirich plant technology resulted in an exceptionally high reproducibility of the quality parameters. The high self-cleaning effect of the Eirich solution made it possible to achieve stable continuous operation without interruption by cleaning cycles, which reduced the amount of waste to a minimum.
The presentation provides an insight into the performance of the Eirich MixSolver® and ContiFeeder® Technology in terms of scale-up and continuous production in Gigafactories.

Material formulation

Optimization of battery microstructures and their electrolyte filling process using pore-scale simulations

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Even advanced battery technologies like lithium-ion batteries (LIB) are still facing a number of technological challenges, especially when it comes to their manufacturing process. An example is the electrolyte filling process which is strongly influenced by physical phenomena that happen on the pore scale of battery microstructures. These are however hardly accessible by experiments such that the filling process is still not very well understood. Since the filling can have a remarkable impact on power and performance, optimization strategies are needed. Amongst those a viable path is modelling and simulation. It can overcome experimental limitations, provide detailed insights, and allows studying large parameter spaces at comparably low efforts.
In this work, we present a simulation framework which is especially favorable for such studies. It is based on a workflow that couples a multi-phase flow lattice Boltzmann method (LBM) to a pore network model (PNM). This coupling is key because it joins forces of the accurate and detailed but computationally demanding LBM simulations and the simple and approximate but performant PNMs. In practice, the coupling is implemented as follows. First, a small set of LBM results is used for calibrating the PNM via a geometrical correction factor. Then, the calibrated PNM is used to accurately predict important material characteristics, e.g., the pressure-saturation behavior.
The LBM-coupled PNM allows for comprehensive insight into the complex dynamics of electrolyte filling. The resulting simulations are computationally very efficient and cheaper than experiments while yielding a high level of detail at the same time. The approach allows to rapidly scan a broad range of combinations of influencing factors to identify those that are most relevant for the electrolyte filling process. It can also be used to inspire new promising material combinations and structural design.
Acknowledgement: This work has been funded by European Union's Horizon 2020 Research and Innovation Programme within the project "DEFACTO" [grant number 875247]. The simulations were carried out on the Hawk at the High-Performance Computing Center Stuttgart (HLRS) [grant LaBoRESys], and on JUSTUS 2 at the University Ulm [grant INST 40/467-1 FUGG].

Dependence of the Electrochemical Performance of LiNi0.5Mn1.5O4 Cathodes on the Conductive Additive for High-Voltage LIB Applications

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Energy storage technology is key for the realization of renewable energy sources and phasing out of fossil fuels. There are still some challenges to overcome in order to realize the large scale production and usage of energy storage worldwide, particularly rapid charging limitations and energy density restrictions. In this study, a cobalt free active material, Lithium Nickel Manganese Oxide, $LiNi_{0.5}Mn_{1.5}O_4$ (LNMO), was employed in the production of cathodes for high voltage lithium ion battery (LIB) applications. LNMO is an attractive cathode active material due to its high operating potential (~4.7 vs. Li/Li+ [1]), non-toxicity and low cost. The practical application of LNMO cathodes in LIBs has been relatively limited, especially for large scale application, due challenges associated with the material (eg. electrolyte decomposition at high voltage, self-discharge and dissolution of the transition metals [2]).
In this study the influence of the conductive carbon additive type and amount on the performance of the LNMO cathodes was investigated. Both the material properties of the electrode (porosity, adhesion etc.) was investigated, as well as the electrochemical properties (through cyclic voltammetry and galvanostatic measurements). The rate capability of the cathode was particularly investigated when prepared with different conductive additive ratios (1.5, 3.0 and 5 wt. %) using carbon black and graphite and pure carbon black. Cathodes with three different densities (2.2, 2.4 and > 3.0 g/cm3), prepared via calendaring, were compared. A non-linear relationship between the density after calendaring and the rate capability was observed for electrodes with conductive additive ratios above 1.5 wt %. The lithium diffusivity was also impacted by both the conductive additive content and density, which could be related to the porosity of the cathode coatings. The capacity loss when the cycling rate was increased also corresponded to the conductive additive contents and cathode porosities.

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Tapped density as a quality control for powder in battery manufacturing

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Granutools

The manufacture of batteries and their improvement is a rapidly expanding field due to the constant demands for reducing CO2 emissions. With the advent of electric cars and renewable energies, storing a large amount of energy in electrical form is essential. The All-Solid-State-Batteries (ASSB) seem to be a promising solution in term of charge density and safety. However, this new technology raises new challenges. Indeed, powders of different natures are used for the construction of electrodes for batteries, especially for ASSB, and requires good properties. Although the chemical properties of the anode/electrolyte/cathode trio are of huge importance, the physical and rheological properties of these powders have an impact on the electrode performances, and therefore on the final properties of the battery. A recent work [1] highlighted the influence of the powder preparation and the manufacturing steps on the battery quality. Powders prepared with different mixing times and different mixing intensities lead different battery performances. However, the parameters relating the properties of the powders, the manufacturing process and the final performance of the battery are not yet clearly established or understood. For this reason, it is important to determine an appropriate method of characterization for quality control of the powders in battery manufacturing.
In this work we show how the tapped density measurement can be used as a characterization method of the quality of a powder. The packing dynamics of different anode powders were investigated with the GranuPack. The experimental protocol is the following: a steel tube, in which is poured the powder, performs a succession of free falls of 1mm of height, called "taps". After each tap, the height of the granular pile is measured by a distance sensor and the bulk density is computed from the knowledge of the tube diameter and the mass of the powder. The bulk density curve as a function of the taps number is then obtained.
This observed that this method is adequate to differentiate various powder mixture. In addition, the measurement is sensible enough to differentiate powders mixtures with equivalent component proportion but with different mixing time. We link these results to the performance of the anodes and the final batteries. As it has been shown that the mixing time of the powder has an impact on the final quality of the battery, our result highlights the great interest of the tap density method for powder characterization in battery manufacturing.

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Microstructural effects during processing

Structure and rheology of electrode slurries and their importance in battery manufacture

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Slurry casting is the most common method of electrode manufacture, and with heavy investment into current manufacturing lines, it will be for some time. It is vital to optimise these lines for best performance and allow rapid adoption of novel, more sustainable, drop-in technologies. In slurry casting, active materials are mixed into a slurry and coated onto a current collector which is then dried, calendared, and assembled into a cell. Currently, these stages are optimised by trial and error and there is a

need for advanced metrology and process understanding to enable in-line control, rapid optimisation, and reduction of wastage in time and materials.
The rheological properties of the slurry are key in the suite of metrology for process control during electrode manufacture, as they offer important insights into the slurry structure and are vital to the microstructure of the final coating. High slurry viscosity creates excess pressure and limits coating speed, elasticity causes instabilities leading to coating defects and high flow causes slumping leading to thin, poorly structured coatings. However, due to differing solvent systems and components, and the complex nature of the many competing interactions, finding the source of these detrimental rheological properties can be difficult. We will discuss the rheology of industrial formulations, the underlying structure that gives rise to these flow properties and how rheological methods, including shear and extension, can be used for process control.

Bridging battery performance ageing and electrode calendering parameters through model-based estimation of tortuosity

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Cidetech Bilbao

Latest electrode manufacturing processes are increasingly taking into consideration its final microstructure improving overall transport of species. An optimization of the calendering process is a key factor during this electrode assembly stage as the coating is mechanically compacted producing a rearrangement of its microstructure and has been investigated trough multiphysics and data driven approaches [1-4].
The tortuosity, along with the porosity, are effective parameters that provide information about the electrode performance at macrostructure level. High tortuosity values affect the behavior of the cells at high currents by significantly decreasing their energy density. Despite its importance, estimating the specific value of the tortuosity of an electrode is very challenging. In fact, it is only feasible to obtain it by indirect measurements. One of the most common ways of estimating tortuosity rely on computing it by means of Electrochemical Impedance Spectra analysis (EIS). This technique consists in processing the performance of symmetric cell in blocking conditions in the frequency domain and fitting it with equivalent circuits or Transmission Line Models (TLM) [5]. The main drawback of this approach is the great influence of both the choice of the specific model and its interpretation.
We present an alternative methodology based on a frequency domain approach of an in-house modified version of the P2D model originally proposed by Newman [6] combined with a data-driven approach. The novel P2D model solved in frequency domain gives a better understanding of the underlying phenomena on the EIS spectra and allows direct estimation of the tortuosity parameter of the manufactured electrode. Additionally, data-driven techniques are implemented to understand calendering effects on electrode's tortuosity and link them to the final battery performance and ageing. In this regard, data analysis techniques, such as Principal Component Analysis, and machine learning models, like Random Forests, have been used.
Finally, NMC622 cathode manufacturing experiments were used as a proof of concept for the proposed methodology, which gives more understanding about the impact of calendering conditions in the final performance and ageing of the cells.

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Stressing of SBR during dispersion and its microstructural effect on slurry and electrode properties

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Due to the rising demand for electric mobility and electric devices, lithium ion batteries (LIBs) have become one of the most important energy storage technology. LIBs consist of anodes and cathodes each with different material systems. The materials are divided into active and inactive materials and, depending on the application, are modified to meet appointed requirements such as fast-charging capability, high energy density or long-term stability. As inactive material polymeric binders ensure the mechanical integrity of the electrode coating and the stability of the slurry both against agglomeration of particles and sedimentation effects. Especially for anodes a suitable combination of material as well as formulation and process parameters is crucial to ensure optimum stability of the slurry, electrode and cell. Typically, anodes are manufactured using carboxymethyl cellulose (CMC) and styrene butadiene rubber (SBR) in a water based slurry, CMC serving as a thickener in the slurry and SBR being responsible for the mechanical stability of the electrode. However, SBR is known to be shear sensitive and hence should be added at the end of the dispersion process. Up until now the effect of dispersing stress and time or specific energy input on the stability of SBR containing slurries is not fully investigated. In respect to industrial manufacturing processes and for both continuous and discontinuous production slurries require continuous stirring if the subsequent coating process does not follow directly in time due to a disruption. Considering all these challenges this study focuses on the stability behavior of SBR in the dispersing process with regard to the resulting slurry and anode properties (e.g. particle size, viscosity, adhesion strength).

Production of solid state batteries

Tailoring solid electrolyte and composite electrodes for large scale production of solid-state batteries

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The progress of promising solid-state batteries (SSBs) with energy densities beyond current state-of-the-art Lithium-ion batteries, which can be manufactured at a large scale, is one of the greatest challenges in the battery industry today. The overall aim is to develop SSBs, suitable for use in high-energy-density as well as high-power applications, electric vehicles, and even aircrafts, which surpass the performance, safety, and processing limitations of lithium-ion batteries. Instead of commercial lithium-ion batteries (LIBs) using organic liquid electrolytes, SSBs employing solid electrolytes (SEs) which perform a dual function of conduction of ions and that of a solid electrode separator in addition of high-energy Li metal (LiM) anode and cathode composite based on high-capacity Ni-rich cathode (NMC). The particular challenge of using a SE is the interface resistance between the battery components. This usually limits either cycle life and/or rate capability of the SSB. In this work, we developed a SE composed of LLZO particles and PEO/PVDF–HFP polymer matrix which shows a significantly improved ionic conductivity up to 2.1×10^{-4} S cm^{-1}, and a NCM622-cathode composite with 1.5 mAh cm^{-2} active material loading relying on scalable solution-based fabrication process. The good processability of pouch cell prototypes, using these scalable cell components, enables manufacturing of competitive SSBs. This work is included within the Orchestra project (GA 101006771), which aims to investigate the suitability of SSBs for hybrid electric aircraft applications.

Upscaling of solvent-free synthesis of sulfide-based solid electrolytes and demonstration of a continuous production process

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All-solid-state batteries (ASSB) as a highly promising technology for potentially safer and higher performing energy storage - especially in e-mobility – experience an unrestrained increase in interest for research and industry [1-3]. Currently, there are still many challenges, such as upscaling the syntheses and processing routes of solid electrolytes (SE) wherefore sulfide-based ASSB have been just established at the laboratory scale. Aiming at the available of high-performance materials, the focus of this work was to evaluate and establish new scalable and in principle continuous processing strategies to produce sulfide-based SE. Sulfide-based SE have attracted broad interest because of their high Li+ conductivity and compliant mechanical properties in ASSB electrodes, but their syntheses are typically known as time consuming processes and mainly require toxic and inflammable solvents [1,4-6]. Within this work, the solvent-free mechanochemical synthesis of Li3PS4 and Li6PS5Cl was investigated and highly optimized in lab scale via high energy ball milling. A deeper understanding of process-structure-product-relations was gained by experiments and associated simulations of stressing conditions with the discrete-element-method (DEM). The coupling of the experimental and simulation results revealed a direct correlation between the existing stressing conditions for different parameter sets and the obtained product properties.
In a subsequent upscaling step based on these findings, the stressing conditions and suitable continuous processing strategies were investigated in scalable mill types. Based on the obtained insights, the solvent-free synthesis of sulfide-based was successfully demonstrated in an upscaled mill type, which will thus facilitate the industrial production of ASSB.

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Characterization of production-relevant properties of all-solid-state battery materials

Timon Scharmann
TU Braunschweig | Institute of Machine Tools and Production Technology (IWF)

All-solid-state-batteries (ASSB) have gained noteworthy attention as a promising replacement for conventional Lithium-ion batteries (LIB) in the near future due to increasing demands in electromobility applications. By deploying solid electrolyte (SE) membranes substituting liquid electrolytes in current LIB, ASSB promote enhanced safety against flammibilty and realize cell concepts with lithium metal anodes (LMA) for higher energy densities. Despite the high variety in potential SE materials, no favorable option for commercialized ASSB production has been identified yet. In addition, these materials exhibit challenging processing properties that have not been adequately characterized previously. In the research presented, different material testing setups aimed to investigate the mechanical and electrochemical behavior of various ASSB cell materials were designed. The designs were derived from established foil testing norms or relevant scientific literature and adapted to the new battery materials. Among tensile, bending and layer adhesion behavior, this also encompasses the resistance against abrasion and puncturing. Next to cathode active materials (e. g. PEO-LFP-LiTFSi) and separators (e. g. LLZO) containing potential SE materials, tests were also conducted with LMA. Cell materials with higher lithium contents displayed higher sensitivities towards any tested load, making an indirect (via substrate material) or damage-free contacting with tools for processing necessary. Also, special care is needed considering process atmosphere, as cell performance deteriorates significantly when using LMA with increased exposure to high moisture containing atmosphere. The acquired results allow the derivation of process-relevant properties for cell manufacturing processes, e.g. electrode behavior during stacking or material contacting behavior during magazine storage. Thus, current battery production processes can be modified and new production processes elaborated.

Slurry production

Process development for continuous extrusion coating of battery electrodes and scale up to pilot scale

Jann Seeba
Fraunhofer Institute for Ceramic Technologies and Systems IKTS

High-load electrodes are considered promising to improve the energy densities of Li-ion batteries (LIB) for mobile applications. Conventional casting processes for electrode coating are limited in terms of film stability and homogeneity, especially for thick, high-load electrodes above 4 mAh/cm² [1]. Additionally, the production costs are high due to long drying times and high energy costs. To tackle these challenges, an innovative extrusion-based coating process is being developed.
The process is based on a twin screw extruder to continuously mix the electrode components with solid und fluid dosing systems. Furthermore, a direct coating of the paste onto a current collector using a slot die is enabled. The solvent content is increased by up to 90% decreasing the energy consumption of the drying process, resulting in a possible overall energy cost saving of 23% [2]. The coupling of mixing and drying saves one process step and reduces further costs. First estimations of possible savings of the cell production cost with the current pilot plant are 2% compared to a conventional process (e.g. slurry based coating), based on the cost model of Schünemann [3]. The process is currently scaled up from a lab process to a R2R pilot plant. In this work we want to present the status of the development. By systematic studies of the formulation (e.g. different binder) and the process parameters the process properties relations are investigated. The coated electrodes are analyzed regarding their quality, homogeneity and inner structure (e.g. coating edge contour, SEM cross section, tortuosity), as well as spatial resolution of thickness, and conductivity and are finally correlated to the extrusion process and formulation. First results show an improved edge contour and maintaining homogenous thickness, while increasing the areal loading above 8 mAh/cm².

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Continuous processing of negative electrode pastes for lithium ion batteries

Kristina Borzutzki
Fraunhofer Research Institution for Battery Cell Production FFB

For efficient production of lithium ion batteries, the growing demands on the production process, particularly a reduction of processing costs which consist of process time, material and energy consumption, must be met. In this regard, the mixing process is of particular importance. Its quality significantly determines the properties of the produced electrode paste and consequently the quality of the subsequent process steps (coating, drying) and finally of the electrochemical performance, including longevity and fast-charging capability, of the fabricated electrodes and batteries [1,2]. Process parameters and equipment setup for the mixing process need to be optimized such that the electrode compounds including active material(s), binder(s) and conductive additive(s) are efficiently deagglomerated, homogenized and dispersed while the generation of particle agglomerates due to insufficient deagglomeration and particle fractures due to excessive energy input is prevented. The state-of-the-art process for electrode paste production is a batch-type process which offers high flexibility particularly beneficial in the field of academic research where novel materials are commonly only available in limited scales. With respect to upscaling and production on industrial scales, though, innovative continuous mixing processes represent a promising alternative since they allow for continuous production of electrode pastes with consistently high quality [3].
Therefore, in this study an innovative continuous mixing process using a twin-screw extruder is investigated for graphite-based aqueous anode formulations for high-power applications. In the context of process optimization, among various process parameters the kneading concentration is identified as one of the key parameters that allows for systematic adaption of relevant properties of the electrode paste (e.g., viscosity and particle size distribution). Varying the kneading concentration for different active materials, a clear correlation to the change in viscosity and particle size distribution can be observed up to a certain re-

versal point where the opposite behavior and a change of the rheological behavior is identified. The underlying mechanism for the observed behavior and its impact on the material and battery cell level is revealed by elaborating further analysis (particle size analysis, scanning electron microscopy, X-ray diffraction and Raman spectroscopy, electrochemical cycling). Finally, it is presented how process and product properties correlate and how monitoring the machine parameters can indicate the observed change of the characteristics of the electrode paste.

Literature

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From lab scale to production scale - upscaling of the continuous mixing process for LIB electrode slurries

Valentin Dolder[1] and Desiree Griessl[2]
[1]Bühler AG, [2]BMW Group

In the last years, the continuous mixing of LIB slurries using twin-screw mixing technology is becoming more popular in the battery industry. Several renowned LIB manufactures as well as research institutes are using twin-screw mixers for small scale lab trials to large scale production. This technology does not only allow to produce conventional LIB electrode slurries but proofs to be an excellent platform for dry mixing of battery materials, too.
BMW Group and Bühler AG are presenting in tandem their view on the continuous mixing technology and will specifically elaborate on the topic of upscaling this process from lab to production scale.
In a first presentation part an introduction on the continuous mixing technology in general and on the collaboration between Bühler AG and BMW Group is given. Furthermore, some practical aspects of upscaling from lab to production scale are addressed by referring to the established continuous mixing projects from Bühler AG at different sites of BMW Group.
The second part of the presentation puts an emphasis on the scientific aspects of the upscaling within the continuous mixing by discussing selected trial results. Here, a focus is set on the parameter "residence time", which is an important parameter for the successful upscaling of continuous mixing systems. In addition, the presentation highlights to which extent the residence time is affected when changing process parameters such as throughput and kneading concentration. A discussion of these process parameters and their influence on battery performance completes the tandem presentation.

greenBatt – Competence Cluster Recycling & Green Battery

Overview & Research Demands

The long-term-oriented Competence Cluster Recycling & Green Battery, launched in 2020, is part of the umbrella concept "Research Factory Battery" of the Federal Ministry of Education and Research (BMBF). It bundles the experience, expertise and engineering infrastructures of 34 research institutes in Germany, which are collaborating in 16 research projects. The cluster's mission is to develop, design and apply innovative technologies, methods and tools for an energy- and material-efficient battery life cycle and closed material and resource loops.
Recycling process chains for traction batteries combine various process steps including dismantling, crushing, mechanical treatment, thermal pretreatment, and pyro- and hydrometallurgical as well as resynthesis processes. The process steps can be combined in various ways to process chains, which compete in terms of efficiency, social criteria and environmental impacts. Major research areas of the greenBatt cluster include flexible and automated dismantling processes, increased safety, improved material yield and purity, prevention of waste and effluents in wet chemical and thermal process routes, innovative refining techniques and the design of sustainable value chains.

Cluster Structure & Research Fields

Figure 1 shows horizontally the structuring of the cluster along the process chain of recycling and resynthesis and vertically the allocation to three core research fields:

- Life Cycle Design & Engineering (coordination by Prof. Christoph Herrmann, TU Braunschweig)
- Process technology (coordination by Prof. Bernd Friedrich, RWTH Aachen University)
- Digitalization (coordination by Prof. Alexander Michaelis, Fraunhofer IKTS)

The greenBatt projects are interdisciplinary and are placed at the interfaces between processes and research fields. The project greenBattNutzung performs an overall system analysis. In addition, there is an interface to the competence cluster Battery Utilization Concepts (BattNutzung) to jointly consider strategies for secondary use.

Figure 1: Structure of the greenBatt Competence Cluster

The greenBatt cluster is funded by the BMBF with around 30 million euros during its initial funding period from 2020 to 2024. Other competence clusters in the umbrella concept for battery research are BattNutzung, ProZell (battery cell production), InZePro (intelligent battery cell production), ExcellBattMat (battery materials), FestBatt (solid-state batteries) and AQua (analytics/quality assurance).

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www.greenbatt-cluster.de

Production of lithium-ion batteries

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POSTER SESSION I Day 1

Battery production 4.0

D1_1.1 Linking Structural Change during Calendering and resulting electrochemical Properties through an Electrode Digital Twin using DEM, voxel-based FEM and pseudo REM Images
Tobias Ohnimus, TU Braunschweig | iPAT

D1_1.2 Application of machine learning methods in the context of cross-process control in lithium-ion battery production
Julia Meiners, TU Braunschweig | IWF

D1_1.3 Location-wise process-based cost model (PBCM) for lithium-ion battery giga factories
Sina Orangi, NTNU

D1_1.4 Ontology-based Battery Production Dataspace and its Interweaving with AI-empowered Data Analytics
Xukuan Xu, Fraunhofer ISC

D1_1.5 Simulative study of accelerated electrode wetting
Johannes Wanner, Fraunhofer IPA

D1_1.6 Traceability in Lithium-Ion Battery Production: Cell-Specific and Marker-Free Identification of Electrode Segments
Inga Landwehr, Fraunhofer IPA

D1_1.7 Efficient experimental data generation for data-driven models by enabling an automatic process parameter variation
Matthias Leeb, TUM / iwb

D1_1.8 Cause-effects in battery cell production – from experience and intuition to data-based process chain optimization
Jonathan Krauß, Fraunhofer FFB

D1_1.9 Traceability in electrode production for optimization of coating processes
Alexander Kreppein, Fraunhofer IPT

D1_1.10 Modular system architecture of an intelligent operations control system for increased product quality in battery cell production
Aleksandra Naumann, TU Braunschweig | IWF

D1_1.11 Synthesis of artificial coating images and parameters in electrode manufacturing by Generative Adversarial Networks
Henning Clever, RWTH Aachen | PEM

Battery supply chains and factory designs

D1_2.1 Efficient and climate friendly energy concept of a battery cell factory
Jakob Palm, Fraunhofer FFB

D1_2.2 Assessing the Supply Chain Criticality of Lithium-ion Battery Cells
Nelson Bunyui Manjong, NTNU

D1_2.3 Status and visions for the emerging battery production industry in Norway; value chains and research environment.
Odne Burheim, NTNU

D1_2.4 Modelling the Costs of Lithium-Ion Battery Cells Based on Virtual and Real Cell Specifications in the ISEA Cell and Pack Database
Martin Florian Börner, RWTH Aachen | ISEA

Electrode production

D1_5.1 Predicting the dispersion progress in twin screw extruders and its effect on electrode and cell performance
Marcel Weber, TU Braunschweig | iPAT

D1_5.2 Unraveling the importance of binding agent characteristics concerning $LiNi_{0.6}Mn_{0.2}Co_{0.2}O_2$-based positive electrode mechanics and cell performance using polyvinylidene difluoride
Johanna Kauling, MEET

D1_5.3 Laser-structuring of Electrodes in Lithium-Ion Batteries – Influence of Structure Topography on fast charging
Maher Kouli, TU Braunschweig | ifs

D1_5.4 Different particle sizes of graphite in multilayer anodes for lithium-ion batteries
Laura Gottschalk, TU Braunschweig | iPAT

D1_5.5 Model Approaches to Predict the Calendering Behavior of Electrodes from Nano-Indentation Measurements for Lithium-Ion Batteries
Sören Scheffler, TU Braunschweig | iPAT

D1_5.6 Numerical Model for Carbon Black Dispersion in Cathode Slurries
Felix Möhlen, TU Braunschweig | iPAT

D1_5.7 Competitive and sustainable dry coating process for battery electrodes
Jannes Ophey, Fraunhofer ISIT

D1_5.8 Evaluation of processing strategies for the manufacturing of Li-ion battery positive electrodes using non-solvent extrusion process
Dane Sotta, CEA-LITEN

D1_5.9 Laser surface modification and micro embossing of high energy graphite anodes for lithium-ion batteries with improved fast-charging capability
Jens Sandherr, Aalen University of Applied Sciences

D1_5.10 High energy density Si@C electrodes: Design, Production and Evaluation of power and energy performance
Jonathan Flórez Montaño, Landshut University

D1_5.11 Laser Structuring in Battery Production for Enhancing the Electrochemical Performance of NMC 811 High Energy Electrodes for xEV Energy Storage Systems
Bernd Eschmüller, AIT

D1_5.12 Influence of Screw Geometry and Solid Content on the Properties of Continuously Produced Si-Anodes
Tim Grenda, TU Braunschweig | iPAT

D1_5.13 Advanced Binders for High Performance Lithium-ion Battery Applications
Buket Boz, AIT

D1_5.14 Stability of multilayer electrode coatings with different properties of the layers
Alexander Hoffmann, KIT | TFT

D1_5.15 Energy efficient anode drying utilizing induction heating of copper current collector foil
Max-Wolfram von Horstig, TU Braunschweig | iPAT

D1_5.16 Investigation of the Drying-behaviour of solvent-reduced granule-based battery coatings
Kevin Ly, KIT | TFT

D1_5.17 Enhanced Electrochemical Stability of $Li_{1.26}Ni_{0.15}Mn_{0.60}Al_{0.05}O_2$ (Al doped-LNMO) as Cathode Active Material for Lithium-Ion Batteries with Enabling High Effective Aqueous Processing
Hongmei Wang, Fraunhofer ISIT

D1_5.18 Analysis of the material- and process-related factors influencing the electrode quality using laser drying in lithium-ion battery production
Sebastian Wolf, RWTH Aachen | PEM

D1_5.19 Innovative Roll-to-Roll Production Process for Metal-On-Polymer Current Collectors
Claus Luber, Fraunhofer FEP

D1_5.20 Study of infrared drying in electrode production for lithium ion battery cells
Jannik Jasper, Fraunhofer FFB

POSTER SESSION I Day 1

D1_5.21 Dry Battery Electrode Manufacturing using a twin-screw extruder for continous powder granulation
Korbinian Huber, BMW AG

D1_5.22 Optical sensors for the highest quality in cell production
Jens Reiser, Precitec GmbH & Co. KG

D1_5.23 Scaling up Electrode Slurries – From Beaker to Barrel
Peter Haberzettl, Mercedes-Benz AG

D1_5.24 Development of an New Dryer Concept for Agile Drying of Battery Electrodes
Jonas Mohacsi, KIT

D1_5.25 Simulation of Dry Processing of Li-Ion Cathodes- from Mixing to Cell Performance Evaluation
Clemens Lischka, KIT | MVM

Electrode, cell and module diagnostics during production

D1_6.1 Spatially resolved resistance measurement of electrode sheets
Martin Böll, Bern University of Applied Sciences

D1_6.2 Challenges of quality assurance and incoming goods inspection for high performance lithium-ion battery cells
Daniel Evans, HELLA GmbH & Co. KGaA

D1_6.3 Detection and evaluation of defect patterns during mechanical electrode slitting
Sebastian Schabel, KIT | wbk

D1_6.4 Multisensory detection of drying monitoring in the electrode production
Dirk Hofmann, Fraunhofer IKTS

Material development and production

D1_8.1 Impact of spheroidization of natural graphite on fast-charging capability of anodes for LIB
Steffen Fischer, TU Braunschweig | iPAT

D1_8.2 New styrene-butadiene rubber (SBR) binder for SiOx anode in lithium ion battery (LIB).
Shoudai Kurosumi, ENEOS Materials Belgium

D1_8.3 Investigation of particulate properties and carbon coating on high-capacity nano-silicon graphite composites
Jannes Müller, TU Braunschweig | iPAT

D1_8.4 Rheological behavior of high Ni cathode materials function of PVDF nature
Gregory and Cyrille Schmidt and Mathieu, ARKEMA

D1_8.5 Revealing the rate-limiting electrode for full cell with high mass loading and C rates
Dimitra Spathara, University of Birmingham

D1_8.6 Tailored polysaccharide binders for aqueous processing of Ni-rich layered oxides cathodes
Simon Albers, MEET

D1_8.7 Multi-scale modeling of Structural Li-ion Batteries
David Rollin, TU Braunschweig | IAM

D1_8.8 Understanding the Influences of Laser Perforation on Thick Electrodes for Lithium Ion Batteries via 3D Microstructure Simulations
Lukas Krumbein, DLR / HIU

D1_8.9 Establishment and application of lithium metal anodes on novel metal-polymer composite current collectors to increase safety and energy density
Julian Brokmann, Fraunhofer IST

POSTER SESSION I Day 2

Cell assembly

D2_3.1 Performance of ultrasonic-welded contacts of metallized polymer foils with insertion of conductive additives
Hakon Gruhn, TU Braunschweig | ifs

D2_3.2 Flexibility and high throughput for the battery cell stack formation – A new machine concept
Sebastian Henschel, KIT | wbk

D2_3.3 Development and Usage of Digital Twins to Optimize Battery Cell Stacking Processes and Machinery
Kamal Husseini, KIT | wbk

D2_3.4 Mini-Environments as an enabler for an economical and ecological battery cell production
Hasibe Turhan, Fraunhofer FFB

D2_3.5 Project "QuaLiZell": Failure Mode and Effects Analysis of Critical Safety Aspects in Lithium-ion Cell Production
Xinyang Liu-Théato, KIT

D2_3.6 Fast Cell-Internal Contacting of Large Foil Stacks Using Micro Friction Stir Spot Welding
Martina Sigl & Alessandro Sommer, TUM | iwb

Cell Types, module and pack design and production

D2_4.1 3D-Printed Cell Housings for Acadamic Battery Research
Paul-Martin Luc, TUB

D2_4.2 Iterative approach for comprehensive optimization of product life cycle by interconnecting packaging and thermal modeling of battery cells; *Moritz Frieges, RWTH Aachen | PEM*

D2_4.3 Evaluation and Comparison of Requirements and LIB-Technologies for Electrified Mobile and Stationary Applications
Vassilios Siozios, Fraunhofer ISIT

D2_4.4 Influence of the cell dimensions on electrochemical cell properties
Robert Löwe, KIT

D2_4.5 Lithium-ion cell format and geometry optimization based on system integration capability and requirements for electric vehicles
Alexander Epp, Volkswagen AG and RWTH Aachen | ISEA

Formation and aging

D2_7.1 Physico-chemical modeling approach to analyze fast charging strategies and aging
Niklas Bless, TU Braunschweig | InES

D2_7.2 Cell-Internal Glass Fiber Sensors for In-situ Temperature Monitoring in LIB
Alexandra Burger, Fraunhofer ISIT

D2_7.3 Data Mining-based Aging Diagnosis of Lithium-Ion Batteries
Ni Meng, Fraunhofer IFAM

D2_7.4 Development of fast charging strategies for lithium-ion battery cells using an electro-thermal model approach
Oliver Landrath, TU Braunschweig | elenia

D2_7.5 Effects of mechanical pressure on pouch-cell performance during formation and cycling
Merit Holdorf, TU Braunschweig | elenia

D2_7.6 Optical and chemical characterization of defects in pouch cells caused by local pressure
Luciana Pitta Bauermann, Fraunhofer ISE

D2_7.7 Effects of electrochemical impedance spectroscopy before and during formation
Torben Jennert, TU Braunschweig | elenia

D2_7.8 Options for fiber optic sensors on lithium-ion cells for prognostic health management under harsh conditions
André Hebenbrock, Clausthal University of Technology

POSTER SESSION I Day 2

Production of next-generation batteries

D2_9.1 Development of a Lithium-ion battery digital twin
Mahshid Nejati Amiri, NTNU

D2_9.2 Novel binders and additives for Zinc anodes in Zinc-Air Batteries
Jeroen Volbeda, TU Braunschweig | iPAT

D2_9.3 Densification of Li3PS4-based separators for all-solid-state batteries by uniaxial pressing
Carina Amata Heck, TU Braunschweig | iPAT

D2_9.4 Evaluation of stabilisation techniques for Ni-rich cathode surfaces in ambient air.
Joanna Galantowicz, University of Birmingham

D2_9.5 Polymer extrusion process for solvent free, scalable production of all solid-state polymer electrolytes
Katharina Platen, Fraunhofer IFAM

D2_9.6 Production of fiber-reinforced electrodes and separators for structural battery composites
Daniel Vogt, TU Braunschweig | iPAT

D2_9.7 Advanced Battery Materials: Processing of Lithium Metal Anodes for All Solid State Applications
Lars O. Schmidt, TU Braunschweig | ifs

D2_9.8 OPTIMIZATION OF HARD CARBON ANODES IN SODIUM ION BATTERIES
Giar Alsofi, University of Birmingham

D2_9.9 Roll-to-roll Prelithiation of Anode Materials- Status & Progress
Benedikt Konersmann, FZ Jülich

D2_9.10 Influence of process parameters on cathode properties of SPAN-based Lithium-sulfur batteries
Robin Moschner, TU Braunschweig | iPAT

Recycling, circular economy and sustainability

D2_10.1 Process Optimization of Li-Ion Battery Recycling
Mahya Nezhadfard, TU Braunschweig | InES

D2_10.2 Fine grinding of pyrometallurgically produced battery slags for dissolving and recovery of lithium
Max Tobaben, TU Braunschweig | iPAT

D2_10.3 Direct Recycling of Electrode Scrap
Sebastian Melzig, TU Braunschweig | iPAT

D2_10.4 Potentials of design modifications to improve the recyclability of lithium ion batteries for mobile applications- An investigation to quantify recycling-oriented design guidelines by means of statistical entropy
Filip Vysoudil, TU Braunschweig | IK

D2_10.5 Data Acquisition and Management in Mechanical Lithium-Ion-Battery-Recycling- An Enabler for Data-Driven Research
Sandro Süß, TU Braunschweig | IWF

D2_10.6 Environmental Assessment of Sulfidic All-Solid-State Battery Pouch Cell Production
Svenja Weber, Fraunhofer IST

D2_10.7 Graphite Recycling from End-of-Life Lithium-ion Batteries Through Heating Processes
Mozaffar Abdollahifar, TU Braunschweig | iPAT

D2_10.8 The Influence of Cationic and Organic Impurities on the Heterogeneous Lithium Carbonate Precipitation
Stephan Musholt, RWTH Aachen | AVT.FVT

D2_10.9 Biopolymer gel electrolytes for zinc-based batteries
David Lammers, TU Braunschweig | ibvt

D2_10.10 Direct lithium-ion battery recycling using dielectrophoretic separation
Jens Glenneberg, Fraunhofer IFAM

D2_10.11 Wet-Mechanical Processing of EoL-LIB to optimize the Recovery of Lithium and other Materials
Moritz Petzold, University of Applied Sciences Münster | IWARU

D2_10.12 Determination of lithium aluminate content in lithium-ion battery slag using short-wave ultraviolet and picture analysis
Sima Hellmers, TU Braunschweig | iPAT

D2_10.13 Challenges and potential approaches for the disassembly of end-of-life traction battery systems in preparation for further mechanical processing
Domenic Klohs, RWTH Aachen | PEM

D2_10.14 Green batteries for clean skies: Sustainability assessment of all-solid-state lithium-sulfur batteries for electric aircraft
Alexander Barke, TU Braunschweig |AIP

D2_10.15 Pyrometallurgical process modelling of slags from lithium-ion batteries based on coupling CALPHAD with finite element analysis
Haojie Li, Clausthal University of Technology | ievb

D2_10.16 Model based assessment of closed-loop battery recycling systems
Steffen Blömeke, TU Braunschweig | IWF

D2_10.17 Thermodynamic modelling of the thermally induced release of electrolyte solvent mixtures in the lithium-ion battery recycling process chain
Christian Nobis, Clausthal University of Technology | ievb

D2_10.18 Impact of adding solid electrolyte interphase constituents as impurities on cell performance of lithium-ion batteries
Anna Rollin, TU Braunschweig | elenia

D2_10.19 Life Cycle Assessment of novel anodes based on Silicon
Cristina Herrero-Ponce, Instituto Tecnológico de la Energía

D2_10.20 Mechanical Processing of LIB Components with the Use of Sensor-Based Material Detection in the Context of High-Quality Recycling
Merle Zorn, University of Applied Sciences Münster | IWARU

D2_10.21 Towards a better recycling of Li-ion batteries by recovery of electrolyte solvents from shredded cells
Lukas Lödige, KIT | TFT

D2_10.22 Inductive heating as a thermal recycling pretreatment for Li-ion electrodes
Michael Wagner, BMW AG and TU Braunschweig | iPAT

D2_10.23 Conceptual design of a condition-based disassembly of lithium-ion batteries- from cell to electrode level
Shubiao Wu, TU Braunschweig | IWF

D2_10.24 Developing robust and scalable recycling routes for cathode active materials in lithium-ion batteries
Lisa Kunkel, Fraunhofer IST

System integration and application

D2_11.1 Lithium-Plating diagnostic and their integration in a battery management system
Mauriz Kahmann, TU Braunschweig | elenia

D2_11.2 Hybrid modelling of Lithium-ion batteries: Proof of concept for application of Physics-informed Neural Network in Electrochemical battery modelling
Soumya Singh, Fraunhofer IPA

D2_11.3 Selection of a separator as an important factor for the safety of a battery cell
Alexander Hahn, TU Braunschweig | iPAT

POSTER ABSTRACTS I Day 1

Battery production 4.0

Linking Structural Change during Calendering and resulting electrochemical Properties through an Electrode Digital Twin using DEM, voxel-based FEM and pseudo REM Images

Tobias Ohnimus
TU Braunschweig | Institute for Particle Technolgy (iPAT)

On our way to a sustainable future we face ever-increasing demands on the performance of lithium-ion batteries. With regard to the optimization of energy density, power density and cycling stability as well as acceleration of battery development, the interest in digital methods steadily increases. The calendering process as one of the last steps in the lithium-ion electrode production chain has a significant impact on the electrochemical properties of the final electrode and consequently on the performance of the battery. Therefore, this work presents a statistical electrode digital twin, which connects the change of an electrode microstructure induced by calendering with the characterization of structural and electrochemical properties.
The formation of the active material structure during calendering is simulated using a pre-existing model based on the discrete element method (DEM), while electrochemical properties are calculated using GeoDict. This commercial software represents the electrode structure consisting of active material particles and a binder network by volume elements (voxels) and solves the differential equations governing electrical flux using a fast explicit jump harmonic averaging solver. Both simulation methods are linked by exchanging pseudo REM images that are generated using python. We present a workflow that combines these simulation methods and allows it to predict electrochemical properties of the electrode such as electrical conductivity or porosity. These properties are further compared with measurements of the electrical conductivity and charge or discharge profiles.

Application of machine learning methods in the context of cross-process control in lithium-ion battery production

Julia Meiners
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Lithium-ion battery production consists of numerous successive process steps with parameters and intermediate product properties that are highly interdependent across all process steps. Due to these interdependencies, propagating defects lead to high costs and rejects. The poster presented depicts the detection and compensation of cross-process defect propagation in process chains using cross-processes control and machine learning methods. Furthermore, an evaluation of a cross-process control system that can be carried out in virtual space is shown, emphasizing the potential of machine learning methods.
For this purpose, use-cases for a cross-process control are defined, a system architecture is derived, the modules of the cross-process control are specified and one module, that describes the use of machine learning, is depicted in detail. First, use cases are defined that detail the application of cross-process control for quality optimization in virtual space. Secondly, the system architecture for cross-process control is derived. This system architecture describes the connection and the data transfer of the cross-process control with further components (e. g. database, process models). In the third step, the functions of the cross-process control are specified in various interconnected modules. Lastly, the module, that depicts the use of machine learning methods for cross-process control, is presented. This module specifies how both data preparation methods and predictive methods are used to optimize process parameters across processes. As a result, the developed cross-process control optimizes quality and significantly reduces rejects along the process chain in lithium-ion battery production.

Location-wise process-based cost model (PBCM) for lithium-ion battery giga factories

Sina Orangi
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In competition with the internal combustion engine vehicles (ICEVs), lithium-ion batteries for electric vehicles (EVs) must fall below a particular value, 100 US$/kWh pack level. In this regard, billions of dollars are injected into the battery industry to enlarge battery cell manufacturing plants in number and production volume, evident in Giga-battery factories worldwide. On the other hand, numerous parameters for the battery production plant need to be considered to reach a high-quality and cost-competitive product. Thus, developing a process-based cost model (PBCM) which has the potential to include simultaneously physical and chemical characteristics of the final battery cell, process parameters, the economic aspects of the location of a battery production plant, and the variability in the prices of critical metals is essential to identify the cost-intensive areas.
Besides, such a method of cost modeling could be helpful not only in finding the minimum efficient scale of a battery production plant and a comprehensive study on the sensitivity of the final product to different parameters.
Driven by this, a process-based cost model for eight different regions has been developed, which includes ten state-of-the-art battery cell chemistries on large scales. For a case study of a 5.3 GWh plant that produces prismatic NMC111-G battery cells, location can alter the total cost of battery cell production by approximately 56 ($/kWh), which is dominated by the acquisition of land and building costs as well as labor cost. Furthermore, comprehensive sensitivity analysis indicates that increasing the plant's production volume and the machinery's recovery period could decrease the total battery cell cost more than other parameters.

Ontology-based Battery Production Dataspace and its Interweaving with AI-empowered Data Analytics

Xukuan Xu, Simon Stier, Lukas Gold, Michael Möckel
Fraunhofer Institute for Silicate Research ISC

As image and sensor based production monitoring has made available large amounts of data along the process chain in battery cell production, artificial intelligence (AI) techniques promise enhanced anomaly detection and new insight into the relevance of observed process deviations. Even though the availability of data is constantly increasing, the complexity and, through specific adaptation, the heterogeneity of the information structures is also growing rapidly. This is especially true for highly variant research, scaleup and pilot production. This poses new demands on data acquisition, data management and data pre-processing. Here, we present a unified framework for integrating an ontology and graph based data space with data acquisition and data analytics to improve data consistency, documentation of workflows as well as the reproducibility of observations and results and illustrate its application to a model Li ion battery cell production facility.

Simulative study of accelerated electrode wetting

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Increasing throughput by shortening process times and reducing energy consumption by simulation are the main challenges in cell production. Here the best possible transparency of the individual manufacturing steps and their physical backgrounds can enable manufacturing improvements. In the manufacturing of lithium ion cells, the electrolyte filling and the associated electrode wetting of the lithium ion cell is a poorly accessible time and quality-critical process. Here, simulation models together with the process framework conditions can bring transparency and can also be used to investigate process improvements. During wetting, process framework conditions such as temperature, ambient pressure and rotation can be used to accelerate wetting. To investigate their effects on process time and wetting, a Lattice Boltzmann fluid model is created and design of simulation experiment methods are used to investigate the effects on wetting rates. Thus, the results can be used to spatially describe the graphite electrode wetting and the capillary electrolyte movements as a function of the process frame conditions. With the help of the presented simulation future product and process technical questions can be derived and answered.

Traceability in Lithium-Ion Battery Production: Cell-Specific and Marker-Free Identification of Electrode Segments

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Traceability of lithium-ion battery components and its process steps to the finished product is utilized to reduce scrap rates and to enable a more efficient production. However, in continuous electrode production, cell-specific identification within the production chain is still a challenge. With regard to the new EU battery regulation, complete traceability with elimination of information gaps between processes down to the material should be ensured. Thus, the Fraunhofer Institute for Manufacturing Engineering and Automation IPA and the Fraunhofer Institute for Physical Measurement Techniques IPM are in the process of further developing and testing an approach for identifying individual electrode segments without identification markers, known as "Track&Trace Fingerprint" using the individual microstructure of the electrode surface. The research is carried out as part of the joint project DigiBattPro 4.0 and implemented at the Center for Battery Cell Manufacturing (ZDB) of Fraunhofer IPA.

Efficient experimental data generation for data-driven models by enabling an automatic process parameter variation

Matthias Leeb

Technical University of Munich | Institute for Machine Tools and Industrial Management

Electrode production for lithium-ion batteries (LIB) is still a broadly researched topic to reduce production costs or identify cause-effect correlations between process and product parameters. Possible approaches are the use of data-driven models like artificial neural networks or simulation models like the discrete element method. Both methods need a proper experimental data basis for the validation or training of the models. Particularly in novel low-solvent or solvent-free electrode production processes, there are unknown cause-effect correlations and many process parameters to consider. Contrary to a relatively large design of experiment, very little electrode material is needed to characterize electrode and coin cell product properties. When processing low-solvent material with a multi roller calender, a high process speed is sometimes advantageous for a homogenous electrode surface and therefore produces lots of electrode material within a short amount of time. A user-defined automatic process parameter variation can generate equally spaced sections of electrode material within a continuous production process where process parameters can be adapted within less than a second. In this presentation, the necessary prerequisites and steps for the implementation of an automatic process parameter variation will be shown.

Cause-effects in battery cell production – from experience and intuition to data-based process chain optimization

Jonathan Krauß

Fraunhofer Research Institution for Battery Cell Production FFB

The advancing climate change requires a shift from conventional energy sources to renewable ones, which is accompanied by the indispensability of an efficient and sustainable storage of electrical energy. This leads to a boom in demand for battery cells. However, the production of battery cells is accompanied by an enormous complexity, as it consists of several subsequent individual processes, each with different quality require-ments. With the goal of producing a high-quality battery cell, knowledge of quality-critical parameters is essential for inter-process quality control and process optimization.
We show how inter- and intra-process cause-effect relationships make a beneficial contribution to the planning of efficient and sustainable battery cell production. Furthermore, we demonstrate, how cause-effect relationships form the basis for a data-based process chain optimization.
Starting point for the cause-effect relationships is qualitative expertise, which is extended by analyzing process data from battery cell production. We show a way how the initial acquisition based on qualitative experi-ence and intuition can be conducted. Subsequently, we present how the initial acquisition is validated and extended, using process data from bat-tery cell production. The cause-effect relationships are constantly updated by automatically analyzing the production data of the digital factory. The electrode production is selected as the basis for valida-tion.
Cause-effect relationships along the process chain form the foundation of an efficient, ecological, and sustainable battery cell production.

Traceability in electrode production for optimization of coating processes

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Battery cells are a key technology to enable the shift from fossil fuels to sustainable energy sources. However, the production of battery cells is highly complex, involving different fields to work closely together. The complexity of this process often results in high scrap rates, which increase the carbon footprint and reduce the efficiency. A solution to this problem can be achieved through the target-oriented aggregation of data that occurs in production and contains information about the quality of the product. To enable this potential, we propose a concept of a traceability system that links data throughout the production process to an individual cell. Subsequently, the traceability system reliably tracks every component of a cell and links quality parameters of the products (e. g. coil, sheet, case) to the production parameters of the machine. In case of defective products, this enables a cell specific data-driven root cause analysis and the storage of insights that led to a defective product in a data base. This enables optimization in terms of quality and sustainability, as root causes for defective products can thus subsequently be identified and removed at an early stage. These concepts are then demonstrated using the coating process of electrodes.
For this purpose, the coating surface quality is tracked by a camera that stores correct and defective coating pictures. The traceability system allocates the corresponding machine parameters (e. g. slot die settings) to the pictures of the respective product. Process engineers and operators are now qualified to link defective coatings (e.g. pinholes) with parameters of the production machine, thus creating the knowledge data base. Newly occurring defects in the coatings can now be compared with existing coating defects. In case of a match an automatic recommendation for a better suited combination of parameters can be derived and displayed to the operator, thus optimizing the quality and sustainability in the coating process.

Modular system architecture of an intelligent operations control system for increased product quality in battery cell production

Aleksandra Naumann

TU Braunschweig | Institute of Machine Tools and Production Technology (IWF)

Due to the increasing demand for electrical energy storage devices, the efficiency and quality of the battery cell manufacturing process chain are becoming more and more important. Special challenges arise due to the complexity of the process chain with numerous interactions between the individual processes, some of which still need to be discovered e.g. through data-based apporaches. To address various production goal criteria (PGC) such as quality, resource efficiency and throughput at once, an in-depth knowledge of the processes and their interrelations is needed. Based on the intermediate product features, downstream processes can be controlled to increase quality rates and reduce scrap accordingly. Therefore, an intelligent operations control system (IOCS) with a data-based approach can be used to find and utilize the connections between process parameters and PGC. For monitoring and controlling the complex process chain, a modular IOCS that can be coupled with a cross-process production control is presented. The system architecture of the IOCS was built with the primary goal of increasing quality rates. To enable flexible production, further PGC are considered.
One module of the architecture is the human-machine interface which enables the display of all relevant information including the comparison of actual and target parameters as well as active parameter submission by a human operator. The machine learning (ML) module however processes production data for prediction. It serves to allow for a production that adapts to changing

PGC while maintaining the same product quality. Predictions based on the knowledge gained through ML are to be used to derive short- and long-term recommendations for action to increase the efficiency of the process chain.

Synthesis of artificial coating images and parameters in electrode manufacturing by Generative Adversarial Networks

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Driven by continuous cost pressure and increasing market requirements, the optimisation of the production of lithium-ion batteries is focus of attention. In order to save time and costs, machine learning (ML) represent a promising tool. ML methods are able to analyse highly complex correlations and abstract data sets. But a considerable amount of training data is needed. Since data is not always available to the required extent, approaches for synthesising artificial data were investigated.
In this study, the quality and corresponding measurement parameters in electrode production were assessed and selected. Based on this selection, coating trials have been conducted and the corresponding data set collected. The data set forms the basis for synthesis of artificial coating images and parameters. The selection and design of the synthesis models was divided into two sub-steps. First, the synthesis of artificial coating images was investigated. This was followed by the consideration of a procedure for the synthesis of structured data sets.
A promising method for data synthesis of (coating) images are Generative Adversarial Networks (GAN). The basic idea of GANs is to oppose two models: a discriminator and a generator. The generator generates artificial data samples that match the input of the training dataset. Afterwards those data samples (both input and artificial data) are introduced to the discriminator. The discriminator's function is to identify whether the data presented originates from the training dataset or whether it is a counterfeit (artificial data) of the generator. The requirements for the synthesis of tabular data sets correspond in principle to those for a multivariate regression analysis.
The combination of the models resulted in a method that allows the prediction of the corresponding measured quality values for arbitrarily selected process parameters, as well as the visualisation of the associated coating result in the form of an artificial image.

Battery supply chains and factory designs

Efficient and climate friendly energy concept of a battery cell factory

Jakob Palm & Jonas Finn Kutschmann
Fraunhofer Research Institution for Battery Cell Production FFB

The goal of Germany is to achieve the greenhouse gas neutrality already in 2045. Companies with existing facilities are encouraged to implement conversion measures as part of a transformation concept to contrib-ute to this goal. The Fraunhofer-Gesellschaft has set itself the goal to achieve climate neutrality in 2030. The Fraunhofer Research Institution for Battery Cell Production FFB therefore needs to establish an efficient and climate-friendly energy concept for the battery cell factory. Obviously, all production processes must be efficient but the way the energy is provided is set by the technical building equipment. For the energy intensive cell production of the Fraunhofer FFB an efficient and climate friendly energy con-cept is essential. To minimize expensive conversion measures in the future, the aim is to optimize the de-sign of the technical building equipment to reduce greenhouse gas emissions. The energy concept also aims for low operating costs.
Due to the strong focus on the construction of a sustainable research facility, a holistic consideration of all components regarding their sustainability takes place. When looking at the different load profiles, the use of dual heat pumps, which can be used for both cooling and heating, is also seen as an opportunity to rein-tegrate existing waste heat into the process and thus further advance the goal of a CO2-neutral research facility.
It becomes apparent that especially the clean and dry rooms, which are required to produce moisture-sensitive lithium-ion batteries, have the highest energy consumption. Already Yuan et al. (2017) found out that for the maintenance of clean and drying rooms 43% of the total energy is consumed to produce lithi-um-ion batteries. Another 39% is required for the drying process, which clearly indicates that the highest energy consumption is needed for the operation of the drying room equipment and drying.
Fraunhofer FFB addresses this challenge even before the facilities are built. For example, mini-environment concepts are being developed to minimize primary energy consumption and the requirement of extensive clean and dry rooms. Different dry room suppliers are challenged on their energy efficiency. The integration of heat pumps for an efficient heat supply for the dehumidification systems is analyzed by simulation.

Assessing the Supply Chain Criticality of Lithium-ion Battery Cells

Nelson Bunyui Manjong
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The transition to electromobility has implications for the supply chains of the raw materials used in lithium-ion battery manufacturing. The supply criticality of these raw material value chains determines the potential risks associated with battery technology development. Our study assesses the supply chain criticality of eleven (11) battery raw materials using the integrated method to assess resource efficiency, otherwise called ESSENZ. Additionally, we study how the criticalities of these raw materials affect ten types of lithium-ion battery (LIB) cell chemistries, further complemented by environmental midpoint impacts performed using Life cycle assessments. For the supply chains, criticalities from cobalt, lithium, nickel, and graphite jointly account for more than 85% of the overall criticality score in the LIB cells containing them. Cobalt dominates the criticality scores in political stability, mining capacity, trade barriers, the feasibility of exploration projects, and the occurrence of co-production. Lithium dominates the criticality score in demand growth, concentration of reserves, concentration of production and primary material used. Nickel dominates the scores in price volatility, while natural graphite dominates the scores in company concentration. For the ten different LIB cell chemistries analyzed, the study develops a quadrant chart matrix showing the relative performance of the LIB cells based on their criticality and environmental impact scores. A transition towards cobalt-free batteries, material efficiency improvements and end-of-life recycling are proposed measures to alleviate some of the criticalities and environmental impacts. The research emphasizes integrating all sustainability dimensions for comprehensive and holistic insights to positively shape the course of action towards a sustainable LIB production system.

Status and visions for the emerging battery production industry in Norway; value chains and research environment.

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Over the past 3-5 years several efforts in Giga scale battery cell production has been launched in Norway, with 3 factories currently being built and in commissioning processes. The industry is targeting somewhat 300 to 500 GWh of annual capacity in in segments from energy oriented batteries to power oriented batteries and including several different chemistries, including lithium ion batteries and lithium ion capacitors. An important aspect for all actors partners are energy efficient and low emission battery production including sourcing materials with the lowest environmental impact possible. This includes for new production technologies and sourcing biobased materials where possible. Accordingly the first research efforts follows around battery production, considering production techniques, value chain analysis, and environmental impacts.

Modelling the Costs of Lithium-Ion Battery Cells Based on Virtual and Real Cell Specifications in the ISEA Cell and Pack Database

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Lithium-Ion battery cells come in various chemistries and form factors, influencing energy density, voltage characteristics, and the cell components' internal structure. The ISEA Cell and Pack Database (ICPD) is a toolbox to collect data from commercially available cells, combining electrical and physical characteristics ranging from OCV measurements to cell disassembly, giving insight into electrode dimensions and material compositions and component weights. In addition to the extensive collection of data from commercially available cells, the ICPD allows us to input "virtual" cells, meaning new materials and cell designs from literature can be created.

A cost tool was developed to compare and evaluate all the cells in the database. The tool reads out characteristic values such as electrode dimensions, coating thicknesses and housing information. It uses data from real production equipment to calculate how many machines are needed to allow for specific factory output. For example, the cathode coating thickness and cathode area are known from the ICPD, making it possible to calculate how long a specific coating machine will need to produce the electrode of one cell. The number of parallel machinery needed can be determined with estimations of the factory's operation and desired output.

The calculation is done for all production steps, giving insight into the total investment costs for all production equipment and additional information regarding the required size of the production building and dry room. All factors are evaluated to determine the production costs per kWh. Based on the material data in the ICPD, adding the material costs gives the full cell costs per kWh and makes it possible to analyse different aspects of the cell design. The effects of cell design parameters on costs can be studied on a mass-production scale.

The poster will present the cost tool and its structure within the ICPD, aiming to discuss the model with other cell production experts from research institutions and the industry. Initial estimations for real cells' costs show the model's capabilities.

Electrode production

Predicting the dispersion progress in twin screw extruders and its effect on electrode and cell performance

Marcel Weber
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State of the art electrode manufacturing lines often rely on discontinuous slurry production processes. Especially with the increasing demand for battery electrodes, the extrusion process for continuous slurry production with its tremendous benefits has caught the interest of both public research and industry. Twin screw extrusion lines combine superior scalability with short processing times and decent dispersing efficiency in a compact form factor. The highly adjustable process further opens new possibilities for process and quality control strategies.

Industrial processes require the definition of predefined quality parameters to ensure a consistent product quality. Based on those quality parameters the process has to be monitored to identify possible faults and inconsistencies. Especially for continuous processes, given the short residence times, detailed product monitoring is key for quality control. In context of smart/autonomous manufacturing a process model is mandatory for the implementation of a cyber-physical system.

This poster will provide insight into the prospective of scalability and control strategies for continuous slurry production using twin screw extruders. This includes results of process studies regarding the scalability and dispersion efficiency as well as the effect of increasing energy input during the dispersion process on slurry electrode and cell characteristics. Based on the results a target parameter for the dispersion progress will be defined. Further insight will be given into the development and implementation of a process model, that allows a prediction and control of the extrusion process. This model will take into account all relevant process parameters.

Unraveling the importance of binding agent characteristics concerning LiNi0.6Mn0.2Co0.2O2-based positive electrode mechanics and cell performance using polyvinylidene difluoride

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The specific energy and performance of lithium ion batteries (LIBs) is strongly influenced by the processing and composition of the positive electrode (cathode). For instance, the mechanical and electrochemical properties are highly affected by varying the individual components of the composite cathode. State-of-the-art cathodes consist of Ni-rich materials such as LiNi0.6Mn0.2Co0.2O2, a conductive additive, and polyvinylidene difluoride (PVdF) as a binding agent and are processed with the organic solvent N-methyl-pyrrolidone (NMP). Properties of binding agents vary depending on the degree of polymerization and chain length, thus influencing swelling rate, intermolecular stability, and adhesion of the composite electrode to the current collector. Therefore, binding agents significantly affect the charge/discharge cycling stability and specific capacity of LIBs. Various binder systems were studied for state-of-the-art positive electrodes processed with NMP or water, however, a deeper understanding of the impact on the electrode properties is yet to be acquired. By varying the molecular weight of PVdF, an ideal ratio of binding agent to solid components (binder coverage of active material and conductive additive) can be identified. Using an extensive binder coverage leads to high internal resistances, whereas a low binder coverage results in weak adhesion to the current collector, leading to a decrease in cycling stability. Therefore, it is crucial to unravel correlations between binding agent characteristics and the electrode properties and performance. In this regard, the initial characterization of different PVdF samples was followed by analysis of the physical electrode properties (adhesion, electronic through-plane conductivity) as well as electrochemical characterization concerning rate capability and long-term cycling stability. Thus, making it possible to tailor binder systems depending on the active material and the associated electrode composition for the specific field of LIB application.

Laser-structuring of Electrodes in Lithium-Ion Batteries – Influence of Structure Topography on fast charging

Maher Kouli
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Electric cars have increased their importance in recent years and have replaced petrol-powered cars. However, when using an electric car, the user expects the same comfort that he is used to. This means, that the range of electrified vehicles should be similar to the range of petrol-powered cars, while at the same time the charging time should be less than 15 minutes within a wide temperature range.

Therefore, the significant increase in energy density is a declared development goal for lithium-ion batteries and their application in electric vehicles. Lithium-ion batteries can achieve a high energy density and very good charge/discharge rates. Unfortunately, these two characteristics compete with each other when it comes to setting the electrode characteristics. However, laser-structuring of electrodes has proven to be a very promising way to enhance the current rate capabilities of lithium ion batteries [Chen et al. 2020; Habedank et al. 2018; Park et al. 2021; Smyrek et al. 2019].

The efficiency of the laser structuring process is highly influenced by the topography of the structure units. Especially the width as well as the depth of each structure unit influences the diffusion processes as the size of the surfaces and the volumes of the structure units differ. In order to optimize the cell performance, it is mandatory to analyze and to understand the influence of the structural unit topography on the current rate capability of lithium-ion batteries.

In order to do so, electrodes with varying structure topographies on electrodes with high areal capacity (~6 mAh/cm²) were created and the effect on electrochemical performance was determined. Based on the structured electrodes, the topography was measured and characterized by laser scanning microscopy, battery cells were assembled and C-rate tests were performed to analyze their fast charging capability. The results show a significant influence on the cell performance.

Different particle sizes of graphite in multilayer anodes for lithium-ion batteries

Laura Gottschalk
TU Braunschweig | Institute for Particle Technolgy (iPAT)

Lithium-ion battery cells with high specific capacity and energy density are one of the current research priorities in industry and science. The challenges of these electrodes are transport limitations within the electrode: lithium ions cannot reach the deeper layers of the electrode coating, which leads to a drop in performance during charging and discharging [1,2]. This phenomenon is a major challenge in the further development of future high-capacity electrodes. One possible solution is to use multilayer electrodes with different layer properties. In this way, pathways for the Li-ions can be created that reduce the ionic resistance of the electrode and ensure an increase in fast charging capability.

This work focuses on two-layer anodes with two different graphite particle sizes ($x50 = 10$ µm; $x50 = 16$ µm). First, both single-layer references and different configurations of two-layer anodes were processed. For the double-layer anodes, the two types of graphite were combined and their amount in the different layers of the anode was varied. The mechanical, electrical and electrochemical layer properties were investigated. However, special attention was paid to the characterization of the structural layer properties by means of impedance spectroscopy and micro-CT. Thus, conclusions were drawn about the pore network and the tortuosity of the electrodes. It could be shown, that the two-layer anodes with a different mixture of both graphite types in the lower layer and only the bigger particles in the upper layer showed a significant decrease in ionic resistance compared to the single-layer reference anodes. One assumption is that by a combination of the different particles sizes a specific number of pores could be created, resulting in an improved pore network and reduced tortuosity.

Influence of Silicon in Silicon/Graphite on the Mechanical and Displacement Behavior of Anodes for Lithium-Ion Batteries

Sören Scheffler, René Jagau, N. Müller, Alexander Diener, Arno Kwade
TU Braunschweig | Institute for Particle Technolgy (iPAT)

Silicon gets into a closer focus of research and development as an innovative active material for anodes used in lithium-ion batteries. As silicon has around ten times the gravimetric capacity compared to common used graphite, here, a huge potential for thinner electrodes and, therefore, batteries with higher gravimetric and volumetric energy densities appears. But with silicon, not only advantages came into the field of batteries. Next to the very high specific capacity a huge volume expansion and shrinking of up to 300% shrinking during lithiation and delithiation comes along. This leads to micro-cracks within the active material particle as well as capacity loss over lifetime. To investigate how to prevent this capacity loss, in this work, silicon-graphite anodes with different weight content of silicon are produced, calendered and analyzed by adhesion strength measurement and micro-manipulation. It can be shown, that silicon has an important influence on the required line load to achieve same coating density during calendering. Furthermore, we are able to show, that silicon-graphite anodes require higher displacement forces at same displacement depth.

Numerical Model for Carbon Black Dispersion in Cathode Slurries

Felix Möhlen
TU Braunschweig | Institute for Particle Technolgy (iPAT)

Batteries play a vital role in the energy transformation from fossil fuels towards more sustainable electrochemical storage systems. In the future, the cell performance increases constantly and new material compounds need to be available.

In the area of battery research, the electrode slurry rheology is an important property, not only for the applicability in the production steps e.g. the coating, but also for the electrochemical performance of the cell. Within the battery process chain the dispersing of the materials is the first crucial step towards a highly functional cell.

State of the art formulations for cathode slurries consist of n-methyl-2-pyrrolidon as solvent, polyvinylidene fluoride as binder, carbon black as a conductive agent and as active material e.g. nickel-manganese-cobalt-oxid. During dispersion, the carbon black is broken down to primary particle size but also smaller aggregates and agglomerates. The effort is to set the ideal particle size distribution, which is not kown. This is important so that, together with the binder, a network is formed which ensures the highest possible cross-linking between the active material and the current collector resulting in a stable and conductive electrode.

Experimental methods of investigation are limited due to physical boundaries and it is not always possible to investigate and prove relationships or assumptions by measurement in real terms. However, the field of simulation has become more and more established in research in recent years as it offers the advantage to investigate e.g. the dispersion process by population balance method.

The poster shows a numerical approach for a dispersion process in a planetary mixer. It addresses the effect of the dispersion process on CB size distribution according to a state-of the art NMC-622 cathode slurry. Therefore, an existing model for high viscosity and highly filled nanoparticle suspensions is adapted for the used planetary mixer. The research demonstrates the required physical properties for the simulation of the dispersion process. Furthermore, the poster dedicates the difficulties and challenges in obtaining necessary input data. First results show a good agreement between the experiments and the PBM.

Competitive and sustainable dry coating process for battery electrodes

Jannes Ophey
Fraunhofer Institute for Silicon Technology ISIT

The fabrication of high-load electrodes is a highly promising approach for increasing the energy density of Li-ion batteries due to a favorable relation of active to inactive materials. However, state-of-the-art tape-casting processes with relatively high solvent contents are limited in terms of coating thickness and drying procedures, accompanied by undesirable effects like e.g. binder migration. Therefore, advanced processes for the electrode production are urgently needed.

Fraunhofer ISIT has developed a dry coating process, which works completely without solvents. The drying of the coated electrode slurry is an energy intensive process. It also requires a large available space because of the long drying sections needed for an optimal process result. With the dry coating process developed by Fraunhofer ISIT, the use of solvents becomes obsolete. Furthermore, higher loadings even exceeding the range of conventional electrodes are possible. This allows a significant cost reduction and additionally results in an enhanced environmental sustainability of the manufacturing process.

The topic of dry coating and its applicability in many product formats is gaining increasing attention among medium and large industrial companies along the battery manufacturing value chain.

In this presentation you will get an insight into an innovative dry coating process as an opportunity for future electrode production.

Evaluation of processing strategies for the manufacturing of Li-ion battery positive electrodes using non-solvent extrusion process

Dane Sotta
CEA-LITEN

Lithium-ion batteries have known a considerable growth as energy storage devices in portable electronics applications, but also in electrified vehicles and stationary systems over the last few years. Cell manufacturers are looking for technical solutions to further reduce the costs of production lines. One of the critical steps is the production of positive and negative electrodes, i.e. the preparation of slurries and coating on current collectors. These complex stages involve the use of solvents that have to be removed during an energy-consuming drying phase. This is of particular importance for the production of positive electrodes where state-of-the-art industrial process is based on the use of carcinogenic N-methyl-2-pyrrolidone (NMP) solvent, which implies the use of safety protocols and equipment for solvent recovery and recycling.

Alternatives to this conventional manufacturing route have been proposed such as extrusion, a well-known process in the plastics industry. Extrusion allows to work with viscous matrices by combining the mixing (homogenisation, dispersion) and film forming (flat die extrusion, lamination) in a continuous way. Generally, the use of solvents is very limited or even eliminated, which makes it an innovative process compared to the standard one. Its industrialisation in the field of batteries therefore seems to be relevant because it combines a continuous process, a small footprint and limited costs.

Here we report the evaluation of two different strategies for the production of porous cathodes for Li-ion batteries without the need of NMP. In one hand, the use of small amount of water in the electrode composition is evaluated and its impact on battery lifetime is characterized. On the other hand, solid blowing agents are directly added in the formulation to create pores by thermally activated decomposition reactions. The impact of these new processes on the electrode morphology is thoroughly characterized with the help of scanning electronic microscope, helium pycnometer and mercury intrusion porosimeter. Electrochemical performances of promising samples are evaluated after assembly of coin and pouch cells. Finally, optimization routes are proposed toward energy-saving and dry processes for electrode manufacturing.

Laser surface modification and micro embossing of high energy graphite anodes for lithium-ion batteries with improved fast-charging capability

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The effect of ionic transport limitation is a well-known problem encountered when increasing the energy density of a battery by using thicker or higher densified electrodes. Because of the resulting decrease in cell performance, several studies are currently investigating new ways to counteract this effect. Ablative trenching or perforation of the electrode layer is a promising approach. However, these approaches go along with a loss of active material and thus, a decrease of the electrode capacity.

We will present two alternative approaches to microstructure the electrodes active mass in order to improve the electrodes performance, both aiming to preserve the active materials.

Electrodes perforated by mechanical micro embossing creating a hole pattern show significantly improved electrode properties, but without material removal and capacity loss.

As another method, it is shown how the electrode surface can be machined by a surface modification using nanosecond laser. A specific adjustment of the laser parameters allows an exposure of surface pores and roughening without substantially ablating the active material.

The differently treated electrodes were subjected to electrochemical analyses such as EIS, C-rate tests and various rapid aging tests. The modified graphite anodes show a lower tendency to Li plating and the degradation is lower. Improvements in fast-charge capability of > 20% are common. Electrochemical impedance analyses with symmetrical cells underscore this finding by showing lower ion transport resistance.

The process development and electrochemical analyses were closely accompanied by microscopic and material analyses, e.g. by white light interferometry, nano-CT and SEM, to reveal the key process-microstructure-property relationships.

High energy density Si@C electrodes: Design, Production and Evaluation of power and energy performance

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It is well known that silicon-based anode electrodes have attracted great interest in the electric vehicle industry due to their high specific capacity (3579 mAh/g), which is ≈ 10 times higher than that of today's graphite anodes. However, significant volume changes during the charging and discharging process and low conductivity have mostly hindered its application in industrial-scale electrode manufacturing.

To overcome these obstacles, we optimised the pilot-scale preparation of silicon-rich electrodes based on core-shell nanoparticles composed of nano silicon coated by a thin carbon layer. Using conductive additives based on graphene nanoplatelets and new water-soluble Fluoroplastics binders prepares a matrix with adjusted viscosity, homogeneity and active material loading, suitable for bulk production of anode layers in a R2R coating process. Their superior performance is partially attributed to the optimized distribution of the nanoparticles on the nanoplatelets, as observed by SEM imaging, which is shown to clearly deviate from common distributions as observed with carbon black. Electrodes with a silicon content of 30% showed excellent cyclability in half-cell with a capacity retention close to 80% (1250 mAh g-1) after 120 cycles at 1C. Moreover, the performance obtained in Ni-rich NCM||Si@C full cells (coin cell format) show an average Coulombic efficiency of 99.8% and capacity retention of 60% after 250 cycles at 2C. Additionally, the influence of calendering and lamination during the pouch cell assembly process is evaluated, revealing a clear improvement for laminated cells.

The results of our research provide an alternative approach for the large-scale production of high-performance silicon-based anodes to increase their energy density, which is inevitable for future lithium-ion batteries.

Laser Structuring in Battery Production for Enhancing the Electrochemical Performance of NMC 811 High Energy Electrodes for xEV Energy Storage Systems

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Novel technologies and production methods are under development in order to enhance the electrochemical performance of Li-ion battery systems to meet ambitious key requirements, e.g., gravimetric energy densities around 700 Wh/l, improved fast charging capability, and reduced capacity fading to enlarge BEV ranges. Layered oxide cathodes, like nickel manganese cobalt oxides (NMC) might provide a satisfactory suitable solution for future BEV energy storage systems [1].

The attempt to reduce the Co-content with a concurrent increased Ni-content in the mentioned NMC cathodes such as NMC 811 are currently focus of recent studies [2].

It has to be considered that NMC cathodes suffer from low high-rate capability and corresponding low capacity retention at high C-rates. This side effects are monitored in further extend for thick film electrode applications.

In order to prevent this, high repetition ultrafast laser ablation is proposed as a most promising and versatile approach. The laser structured 3D electrode surface enhances the liquid electrolyte wettability and reduces cell overpotential at high power operation. Additionally, the lithium-ion transport pathway is reconstructed which leads to improved overall ion diffusion kinetics [3].

The overall approach is to advance the electrochemical performance of batteries using thick film Ni-rich NMC811 cathodes and graphite anodes on different cell configurations, coin cells, single-layer pouch cells, and multi-layer pouch cells, respectively, by using this novel laser pattern technique in combination with NMC811 powder stabilisation. The prime focus is on the scale-up feasibility of the electrode production along with the integrated, continuous roll-to-roll structuring in order to produce next generation NMC batteries with significantly improved performance characteristics. This work was performed under the frame of the RealLi! project, in which the following aspects are covered:

1)Development of thick film NMC811 electrodes with high areal capacity.
2)Passivation approach to improve cycle stability and lifetime.
3)Cell assembly and electrochemical characterization.
4)Holistic evaluation of the potential environmental impact of the NMC811 cells via life cycle assessment.
5)An experimentally validated electrochemical model to describe electrode structures and their optimization.
6)Improved electrochemical performance of NMC811 electrodes on a laboratory scale by using 3D laser structuring.
7)Scale up of the electrode structuring process and corresponding improved electrochemical performance of NMC811 electrodes in pouch cell format by using 3D laser ablation.
8)Holistic performance comparison of the produced cells in different cell configuration levels with and without structured electrodes.

Acknowledgments:

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Influence of Screw Geometry and Solid Content on the Properties of Continuously Produced Si-Anodes

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Lithium-ion batteries are the leading technology for energy storage. Intensive efforts have been made to improve the energy density of lithium-ion batteries, especially through the use of active materials containing high capacity silicon. But the influence of dispersing process like the solid content during kneading and the screw configuration with its specific energy input (Em) and stress intensity into material are also crucial for the performance of the battery. Therefore, in the future, the focus will be on the continuous production of battery slurrys (extrusion) in which higher stress intensities and a higher throughput can be applied.
The quality of the electrode depends largely on the dispersion process. The success of the dispersion process depends largely on the specific energy input, the stress intensity and frequency. Thereby high Em's can result in a reduction and coating of the carbon black particle size and can lead to an improvement of the conductivity of the electrodes. However, too high specific energy inputs can also lead to possible damages to the active material, deagglomeration of carbon black particles and to resulting capacity losses during battery operation. For this reason, the main objective of this study is to compare the specific energy input and stress intensities at different screw configurations and solid contents during a continuous extrusion process. A modeling approach which determines the stress intensity depending on the viscosity will also be applied to describe the relationship between particle sizes and Em. To this effect, slurries are prepared in a continuous extrusion process and are investigated with respect to their particle morphology and rheological properties. To have a closer look on the stressed slurries, the physical and electrochemical properties of resulting electrodes are analyzed. The electrochemical performance of the manufactured Si-Anodes are represented with an area capacity of 4 mAh/cm2 in full cells.

Advanced Binders for High Performance Lithium-ion Battery Applications

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The selection of polymer binders is highly crucial for the electrode fabrication process, providing mechanical strength while maintaining the electronic and ionic transfer during cycling. The current state of art for binders are mostly based on polyvinylidene fluoride (PVDF) for positive electrodes in toxic organic solvent N-methyl-2-pyrrolidone (NMP). In addition to the hazardous environment, these types of binders are not suggested for high voltage battery applications due to their low adhesiveness, weak mechanical strength, and poor functionality [1].
Especially for generation 3b cathode materials, namely lithium nickel manganese oxide (LiNi0.5Mn1.5O4, LNMO) spinel high voltage cathode or lithium nickel manganese cobalt oxide (NMC) high capacity cathode, building a stable cathode electrolyte interphase (CEI) plays an important role for the overall cell performance and cycle life. In the first formation cycles, active Li is lost due to the side film formation on the anode. To counterbalance the Li loss, an ionic binder in which covalently bonded Li is incorporated with the polymer can be a promising solution. The requirements of high energy density batteries make essential the exploration of advanced polymeric binders, which possess particular functions. For instance, the ionic polymer is blended with the active material which ameliorate the electrochemical polarization of interfacial resistance. There are excellent examples for specifically on lithium iron phosphate (LiFePO4) [2] cathodes whereas, only limited number of studies for LNMO and NMC cathodes [3].

In this work, we aim to synthesis a polymer binder by using a widely known polyacrylic acid (PAA) backbone with covalently bonded Li cations. One of the main advantages of the LiPAA binder is that is soluble in water, thus, this application does not contain volatile organic solvents. Both NMC and LNMO cathodes are processed water-based and contain an active binder. That way we produce environmentally friendly high capacity and voltage cathodes while improving the overall battery performance.

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Stability of multilayer electrode coatings with different properties of the layers

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Multilayer electrode structures are a central component of the current optimization of lithium ion batteries and their manufacturing process (Diehm et al. 2020a; Chen et al. 2021; Jobst et al. 2020). The advantages include improved cell properties through the multilayer combination of different active materials, faster drying through the graded distribution of binders and improved adhesion of the electrode to the collector foil through adjusted binder contents or even the use of a primer layer (Diehm et al. 2020a; Diehm et al. 2020b). Usually, the different materials also influence the rheological properties of the fluids. In order to ensure a defect-free coating, the formulations are usually adjusted so that the viscosity differs only slightly. For this purpose, passive components are added to the material systems which are disadvantageous with regard to the electrochemical cell performance. These adjustments may not be necessary at all, since a stable coating can be achieved even with developed viscosity gradients. However, due to the shear thinning properties, there is an additional influence of the speed on the rheology. In combination, the multiple influencing variables have to be combined in a model to allow conclusions to be drawn about the production process and the scalability.
In this poster, experimental studies on the coating stability of multilayer coatings with battery slurries and model systems are presented. Focus is set on the operability limits, such as the lower limit of bead breakup and the upper limit of leaking. Both, the ratio of viscosity and also the ratio of wet-film height have an impact on the coating windows but stable films can be achieved at wet-film-height or viscosity ratios different from unity. Another criterion for comparison is given by the degree of shear thinning. For this purpose, the investigation is extended to newtonian model systems. The experimental results are compared to various calculation models. First, calculations are performed with common analytical models. As a next step, a numerical model is introduced that considers the nonlinear influences of viscosity on the velocity field and therefore on the coating window.
This work contributes to the research performed at the Material Research Center for Energy Systems (MZE). The authors would like to acknowledge financial support of the Federal ministry of Education and Research (BMBF) via the project "ForeCast" (Grant number: 03XP0402B).

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Energy efficient anode drying utilizing induction heating of copper current collector foil

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Reducing the energy consumption during the production of lithium-ion-batteries (LIB) is critical to meet the increasing demand of flexible and efficient energy storage while reducing the carbon footprint of the energy infrastructure. The electrode drying is one of the most energy intensive processes in the LIB production chain providing the leverage for optimization.
Conventional convective dryers utilize the energy inefficiently as they use air as a medium to transport the heat to the coating to be dried. The evaporating solvent is carried away with the hot air alongside a significant portion of the heating energy.
Drying via heat conduction, in contrast, has little energy losses as it heats the electrode without using a medium for the heat transfer. To implement this drying technology into an industry standard coil-to-coil process, induction coils (IC) are used for contactless heating. The ICs heat up the current collector foil (CFF) through joule heating. The CFF subsequently transfers the heat via conduction to the coating. The temperature of the convective dryer can be reduced significantly leaving it with the main task to transport the solvent away from the coating surface to be dried.
Here, we present first results of this novel approach. While utilizing a single induction module with a maximum power of 5 kW, anodes with an areal loading of 15 mg/cm² have been produced at a web speed of 2 m/min. The temperature of the pilot scaled coil-to-coil convective dryer with a length of 6 meters was reduced to 30 °C. The anodes show comparable adhesion strengths, electrical resistance and electrochemical performance compared to reference anodes produced by conventional convective drying at 60 °C.
While this approach comes with challenges in process control and parameter optimization, its focused energy input offers the potential to significantly reduce the needed dryer length or increase the web speed, leading to additional significant energy savings.

Investigation of the Drying-behaviour of solvent-reduced granule-based battery coatings

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Lithium-ion batteries have become an indispensable part of modern life. Due to their high energy and power density, lithium-ion batteries are expected to be used primarily in the field of electromobility in the future. The desire for higher performance, cost efficiency and safety poses various challenges for the automotive industry and battery research.
The drying process of battery electrodes has an enormous influence on the electrode quality. It deter-mines electrode characteristics and most importantly cell performance. The major problem during dry-ing is the migration of binder to the electrode surface, resulting in an inhomogeneous binder-distribution throughout the film.
As for state of the art electrodes, drying is one of the most cost-intensive process steps, a new ap-proach for reducing the solvent content in electrode-processing and therefore increasing the cost-efficiency for the battery manufacturing process will be investigated in this work. By reduction of sol-vent content and the usage of granulates in battery-paste manufacturing, the storage stability of the produced electrode pastes is several weeks. This leads to a decoupling of paste and electrode produc-tion and a significant increase in production flexibility.
In terms of the drying step it is essential to investigate the influence of the highly-concentrated particu-late granular system on the drying process. Especially the influence on pore structure, film consolida-tion and binder migration is crucial for understanding the drying process. For this purpose, a series of fundamental studies will be conducted. This work presents the experimental methods for the investiga-tion of the drying behaviour under defined process conditions. These are mainly gravimetric drying tests and investigations by means of cryo-SEM for the elucidation of the pore emptying mechanism, as well as investigations with a magnetic suspension balance for the disclosure of the sorption behaviour. First experimental results will be shown.
This work contributes to the research performed at CELEST (Center for Electrochemical Energy Stor-age Ulm Karlsruhe) and Material Research Center for Energy Systems (MZE). The authors would like to acknowledge financial support of the Federal ministry of Education and Research (BMBF) via the InZePro cluster-project “GranuProd” (Grant number: 03XP0344C). In addition, the authors would like to thank ARLANXEO Deutschland GmbH for providing the binder used in this project.

Enhanced Electrochemical Stability of $Li_{1.26}Ni_{0.15}Mn_{0.60}Al_{0.05}O_2$ (Al doped-LNMO) as Cathode Active Material for Lithium-Ion Batteries with Enabling High Effective Aqueous Processing

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The high-voltage $LiNi_{0.5}Mn_{1.5}O_4$ (LNMO) spinel is a promising candidate as an active material of the positive electrode in lithium-ion batteries. [1] Many research activities are focusing on it, despite the low cycle stability obtained so far and the high intrinsic resistance, which leads to high impedances in the cathode since the high operating voltage (>4.7 V) of the LNMO allows for energy densities similar to, or even higher than current NMC based Li-ion batteries, while eliminating cobalt. [2-3] An effective method to solve this problem is coating or doping of other elements. [4] The most studies on LNMO based cathodes have involved PVdF-based binders that necessitate the use of toxic and expensive N-Methyl-2-pyrrolidone (NMP) as solvent. Water-based electrode processing of lithium-ion cathodes is one of the key steps towards environmentally friendly battery production [5].
This study presents a water-based processing of homogeneous, and stable cathode coatings with $Li_{1.26}Ni_{0.15}Mn_{0.60}Al_{0.05}O_2$ (Al doped-LNMO) as active material. The electrodes were processed directly on aluminum foil using water as solvent for slurry preparation. The electrodes were prepared with sodium carboxymethylcellulose as the only binder. Phosphoric acid was used to adjust the pH-value of the slurry to avoid the loss of capacity due to the lithium-proton exchange in aqueous solution. The water-based approach leads to stable cycle performance and excellent coulombic efficiency of 99.08 % with the current density of C/10 after 100 cycles and a specific discharge capacity of about 199 mAh/g. By further optimization of the initial formation cycle, these electrodes offer an electrochemical performance exceeding with promising stability for pouch cells testing, which are considered very promising for the realization of next-generation cobalt-free lithium-ion batteries. This work portends that this highly effective and easy-to-process method can be implemented into the electrode manufacturing process without any additional steps.

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Analysis of the material- and process-related factors influencing the electrode quality using laser drying in lithium-ion battery production

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The coating and drying process is currently responsible for about 38 % of the energy consumption for lithium-ion battery cell production. The process technology of laser drying offers the potential to substitute energy-intensive convection drying. As a result, a significant reduction in energy consumption in battery production can potentially be achieved and CO2 emissions saved. Nevertheless, there are still various challenges such as binder decomposition due to excessive energy input, which makes it essential to identify the factors influencing the laser drying process on the material and process side by means of test series in pilot line scale.

In this poster, the results of experiments on drying anodes using lasers are compared with the results of convection drying. An 8 kW high power diode laser was used to dry the anodes. The laser intensity was varied in a roll-to-roll process and web speeds from 0.8 to 4 m/min were used. The electrodes were investigated on the basis of quality parameters such as residual moisture or maximum tensile stress, and both process-side (e.g. laser intensity, web speed) and material-side (e.g. material composition) factors influencing drying quality are identified.

Innovative Roll-to-Roll Production Process for Metal-On-Polymer Current Collectors

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As electro mobility is becoming more and more mature, the demand for safe and environmentally friendly batteries is rapidly growing. Due to the high market growth of batteries, a shortage of resources, e.g. metals, can be foreseen. To avoid this and to increase intrinsic safety of the battery cells, Fraunhofer FEP, in collaboration with VON ARDENNE GmbH, developed the deposition of thick metal films onto polymer substrates for use as current collectors in lithium ion battery cells as replacement for the metal foils currently used.

Combining the two aspects of novel material combination and novel production technology, the use of an electron beam deposition process to deposit thick metal layers (up to 1 µm thick) on thin polymer substrates (down to a thickness of 6 µm) by using of cost efficient Roll-to-Roll technologies has been demonstrated. To tackle the problem of excessive substrate heating during the process, a novel cooling method, provided by VON ARDENNE GmbH, is being used.

Dynamic deposition rates for Aluminum of around 25 000 nm*m/min for a width of 500 mm were achieved. Current Collectors with sheet resistances down to 35 mOhm per square on both sides (top and bottom) were fabricated.

The shown industry compatible Roll-to-Roll process is fully scalable and the double sided deposition of roll lengths of up to 1000m could already be demonstrated.

In the poster, we present recent results and possibilities for further upscaling of the process.

Study of infrared drying in electrode production for lithium ion battery cells

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In view of the increasing number of battery cells produced and the customers demand for more sustaina-bility in the products, there is an increasing importance to reduce the energy consumption in the produc-tion as far as possible. [1] In addition to the ecological aspects, the economic aspects are also of great importance for the manufacturers of the battery cells, such as process time, production costs, system investment and system footprint. One of the biggest influencing factors on ecological and economic as-pects in battery cell production is the electrode drying process, as this is one of the most energy-consuming processes in the battery cell production. [2] In a conventional manner a hot-air drying oven is used for the drying process. In the oven, the coating is heated via convection in order to evaporate the solvent out of the coating. Since the residence time of the electrode foil in the roll-to-roll process in the oven is around 40- 80 seconds, the oven could reach a length of up to 100 m or more. [1] In addition to high investment costs for the oven, these large ovens also result in massive operating costs due to the large energy requirement. Furthermore, the space required for the drying process is one of the largest in battery cell production. [1]

In order to improve the electrode drying process, innovative process technologies are currently being inves-tigated, but they are not in installed in the factories yet. One of the most promising technology alternatives is infrared drying.[3] The coating is heated via electromagnetic waves in the infrared range. The radiation is not completely absorbed by the surface but penetrates deeper into the coating and heat it more evenly. This more direct and faster form of energy impact can significantly reduce the processing time, which significantly reduces the space and the energy required. [3]

With this fast and direct energy impact, attention must be paid to the quality of the electrode.[1] Since this process technology is not used in conventional battery production lines, this study focuses the validation of this technology for different materials and machinery settings. Therefore, the quality of the dried electrode is examined. For this purpose, an infrared module is integrated in a roll-to-roll process in addition to the conventional hot air oven. This module can be operated both in combination with the convection oven (booster) and alone without the oven. The optimal system settings are determined systematically for a specific electrode recipe in order to dry the electrode with little energy impact in the shortest possible time. The quality of the electrode in terms of adhesion, residual moisture and electrical properties is constantly checked and compared with the quality of conventionally dried electrodes. Furthermore, mathematical models are applied and validated with the experimental data in order to generate a basic understanding of the process and material and thus to be able to design the drying process more focused for current and future materials.

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Dry Battery Electrode Manufacturing using a twin-screw extruder for continous powder granulation

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BMW AG

Electrode manufacturing is a cost- and energy-intense process that relies on the use of a hazardous and expensive solvent, N-methyl-2-pyrrolidone (NMP), for cathodes. After coating the battery-slurry to a current collector, the solvent needs to be evaporated to obtain a porous electrode suitable for the use in a Lithium-Ion Battery, meaning that the solvent is a processing material and unwanted in the final product. Nevertheless, the utilization of NMP demands costly labor protection and explosion safety measurements during mixing and coating and necessitates a highly energy and floor-space demanding drying step using thermic drying ovens of up to 100 meters.[1] For ecological and economic reasons, NMP is not emitted in large-scale production facilities, but condensed and recovered by an elaborate distillation process to receive battery-grade NMP. The NMP-recovery system adds additional floor space and energy demand to the production site. The drying and solvent recovery can account for up to 39% of the total energy demand of a Lithium-Ion Battery Cell production and therefore produce significant CO2 emissions.[2] A solvent-free, dry electrode manufacturing that eliminates the use of solvents hence reduces the floor space, energy demand and cost of a Lithium-Ion Battery production and eases safety and environmental concerns. Different approaches have been reported in the literature to put dry coating into practice,[3],[4] yet most strategies lack of a feasible implementation into large scale production. In contrast, a dry coating approach that is sometimes referred to as the Maxwell-Process is, according to media reports, currently installed at Tesla’s Gigafactory in Berlin.[5] Compared to the state-of-the-art electrode manufacturing process, dry coating requires different polymeric binder systems that form spiderweb-like structures of fine fibrils connecting the electrochemical active particles and the conductive additive particles. The fibril-network is primarily formed by a high-shear dry mixing process. The powder mixture is then compressed to a free-standing electrode film (powder-to-film) by a heated rolling mill (calender) and the resulting film is ultimately laminated to a current collector foil (film-to-foil). We demonstrate that a twin-screw extruder can be used to tune the degree of binder-fibrillation during dry-mixing of NMC-based cathode mixtures and show a superior cycling-stability of dry-coated cathodes in single-layer pouch cells compared to wet coated reference electrodes of likewise composition and electrode design. Additionally, the requirements towards current collectors to guarantee a sufficient adhesion of the free-standing foils were studied in detail.

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Optical sensors for the highest quality in cell production

Jens Reiser
Precitec GmbH & Co. KG

Precitec stands for the passion for light, which we make use of in the fields of optical measurement, laser cutting and laser welding. This presentation focuses on our solutions for optical sensors. In a first part, the physical background of our sensors such as the chromatic confocal or the interferometric measuring techniques will be displayed. These techniques enable resolutions < 1 um.
Our sensors allow the inline and contactless measurement of critical quality criteria in the field of cell production. So in a second part of the presentation, topics such as (i) the detection of impurities (e.g. particles in the range of 10 – 50 um; or electrolyte in the wet and crystallised condition), (ii) the measurement of thickness and edge superelevation (also directly after the slot die, i.e. in wet condition; cathode side: ATEX certificate), as well as (iii) the inspection of the cutting burr will be discussed.
The presentation closes with an outlook of possible closed-loop strategies for tomorrow's MP lines.

Scaling up Electrode Slurries – From Beaker to Barrel

Peter Haberzettl
Mercedes-Benz AG

This poster shows the upscaling processes of lithium-ion slurries under rheological and other processing criteria. Slurries from low-volume centrifugal planetary mixers (e.g. Thinky Mixer or SpeedMixer) are analyzed and the mixing process is transferred to a larger intensive mixing system in order to recreate the slurry with the same qualitative criteria.

Development of an New Dryer Concept for Agile Drying of Battery Electrodes

Jonas Mohacsi
Karlsruhe Institute of Techology

The increasing demand for energy storage may position battery cells as one of the main players in the process of the energy transition concerning aspects like e-mobility. For this purpose, it is essential to optimise the manufacturing process in terms of energy and material efficiency as well as cell quality. A decisive step in the manufacturing process of the battery electrodes consists of reducing the solvent loading by means of a suitable drying process. To meet the future challenges in terms of flexibility, efficiency and quality, an optimised concept of a convective dryer is being developed.
Essential for uniform and efficient convective drying is a homogeneous distribution of the heat transfer coefficients on the film surface. Therefore, the focus is initially on researching suitable drying nozzles. With the help of flow simulations and tests using thermochromatic liquid crystals (TLC), it was possible to develop and optimise a nozzle geometry that is characterised in particular by its agile applicability. As the nozzle height, slot width and angle of incidence are variably adjustable, the distribution of the heat transfer coefficients on the film surface can be flexibly selected. Due to a free positioning and interchangeability of individual nozzles, the developed concept offers the possibility to integrate inline sensors into the drying process, that enables an inline monitoring of the process parameters, which is the basis for a real-time quality management. In addition, the flexible concept offers the option of integrating modules (IR/LASER) for alternative heat input. A variable recirculation valve enables active control of the humidity of the drying air. To increase the energy efficiency of the dryer, a heat exchanger is integrated to recover the heat from the exhaust air. This was designed, developed and optimised with the help of flow simulations.
This work contributes to the research performed at CELEST (Center for Electrochemical Energy Storage Ulm Karlsruhe) and Material Research Center for Energy Systems (MZE). The authors would like to acknowledge financial support of the Federal ministry of Education and Research (BMBF) via the Prozell cluster-project "EPIC" (Grant number: FKZ 03XP0295A) and AQua cluster-project "IQ-El" (Grant number: FKZ 3XP0359A).

Simulation of Dry Processing of Li-Ion Cathodes - from Mixing to Cell Performance Evaluation

Clemens Lischka
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For the conventional production of Li-Ion battery cathodes several process steps are commonly used. One of which, the wet mixing, is commonly using a solvent like N-Methyl-2-pyrrolidon (NMP) which is a hazardous liquid and on top energy intensiv to get rid off after the cathode is coated on the conductive foil. Research is therefore recently intensified to establish a process that is completely relying on dry processing without involving any solvent. Since the dry mixing process becomes the major influence for the cathode structures in such a process, a simulation approach is used here to study the mechanics of dry mixing. Especially the machine parameters like mixing time and speed of the used mixing equipment have an important influence on the quality of the mixed cathode materials. To establish a connection between mixing performance and electro-chemical performance of the electrode a coupled simulation approach is used. In this approach the cathode materials are mixed and the resulting structures and compositions of the cathode are then fed into a second simulation platform to construct electrodes on the basis of the previous dry mixing simulation. With this coupled approach a direct connection between the first process in the cathode manufacturing, the dry mixing, and the finished electrode cell is established.

Electrode, cell and module diagnostics during production

Spatially resolved resistance measurement of electrode sheets

Martin Böll, Michael Stalder, Severin Herren, Axel Fuerst
Bern University of Applied Sciences | Institute for Intelligent Industrial Systems

An important way to reduce Lithium-Ion battery cell cost is to reduce the production scrap rate, such that less of the expensive raw material is thrown away in faulty product. To achieve low scrap rates important characteristics of intermediate products, need to be checked along the manufacturing chain, and the information must be fed back to the process to take corrective actions. Currently manufacturers use various imaging technologies, such as X-ray radiography , X-ray tomography, ultrasonic scanning to, e.g., supervise electrode coating profiles, electrode arrangement in a fully assembled cell [1–3]. However, there is a lack of measurement methods to characterize a single electrode sheet before it is stacked. Access to such information would be very valuable, since one faulty electrode sheet can ruin an entire cell with hundreds of electrode sheets.
In this contribution we propose a method to measure the resistance of electrode sheets spatially resolved. The method uses the 4-wire method and can be applied for electrode surface to current collector measurements, or electrode surface to electrode surface measurements for double-side coated sheets. Further, we demonstrate how the gathered measurements can be used on following cases: 1) Identify non-conforming electrode sheets which can subsequently be removed from the manufacturing process, 2) Cluster sheets with similar characteristics to assemble cells of different grades, and 3) identify defects in separator layer of catholyte sheets (cathode and solid electrolyte composite).

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Challenges of quality assurance and incoming goods inspection for high performance lithium-ion battery cells

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The incoming inspection of lithium-ion battery cells is a great challenge for manufacturers of battery systems as the battery system provider is eligible for the quality and reliability on system level.

While assembly of the battery system and the respective processes are closely monitored, process quality on component level is usually out of the scope of the battery system provider. The process is supervised by the component suppliers' quality assurance, unless the components (e.g. BMS, housing, sensors) are also manufactured by the system provider. However, to secure the reliability of the supplied battery cells, incoming inspection can be performed in addition to the suppliers' quality assurance efforts. Common measurement methods, which determine the quality of the battery cell e.g. rely on measuring the cells internal resistance [1], 1kHz resistance [2] and the open-circuit voltage [1,3]. The methods require short testing times and are therefore capable to comply to tough cycle time requirements in series production. Unfortunately they are limited in their capability to deliver a deeper insight into the quality of the cell. While these methods generally enable a classification, not all manufacturing defects, that have an impact on the cells performance and lifetime can be detected. Therefore, defective cells might pass the incoming inspection and have a negative impact on system level or even possess a safety threat.

As a result more comprehensive but also time intensive test procedures were developed, considering e.g. capacity measurements and electrochemical impedance spectroscopy (EIS) [2,3]. This offers a promising perspective to improve incoming goods inspection. Until recently the applicability of EIS as in-line approach was limited, as testing times would exceed common cycle times in battery system manufacturing. However, advances in EIS measurement have shown that measurements could be performed in shorter time [4] and potentially within the cycle time requirements.

Therefore, we assess the potential of EIS as incoming goods inspection. We compare the method to state of the art approaches and analyze its ability to grade the cell quality and identify crucial defects. In support of the comparison an experimental analysis of more than hundred battery cells from one production batch is performed.

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Detection and evaluation of defect patterns during mechanical electrode slitting

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The process chain for the manufacturing of modern Li-ion battery cells includes numerous complex, currently immature production steps. One of these production steps, at the interface between electrode production and cell assembly, is slitting of the coated and calendared electrode foils. Within the mechanical shear-cutting process, defect patterns such as cracks, delamination, burr formation and waviness can occur in the cutting edge areas. These defects can negatively affect the process capability of downstream production steps, such as stack formation, as well as the performance and safety of the cells. In addition to that, decreasing material waste by reducing scrap in early stages of the production is becoming more and more important to safe the rare and cost-intensive raw materials.

This work investigates the influence of plant-side process parameters on defect patterns (especially the waviness) at the anode and cathode cutting edges. Therefore, web speed, web tension, blade overlap, state of the blade sharpness as well as the contact force between the blades are analysed on an industrial roll-to-roll slitting machine. In addition, the particles generated during the mechanical cutting process are collected and characterized in terms of size and material. The offline analysis of the cutting edge characteristics is carried out using light microscopy. Integrating an optical laser triangulation sensor into the slitting machine provides a new method for enabling the in-line detection of the cutting edge topography. It turns out that the cutting edge quality depends essentially on the orientation towards the cutting knives as well as the blade geometry. The electrode cutting edge enclosed by the pair of knives shows significantly less waviness than the cutting edge facing away from the cutting knifes. In addition, it is shown that the waviness can be optimized by minimizing blade overlap. Subsequent investigations will also take the material parameters into account and focus on the in-line monitoring of cutting tool defects that may result from wear or misuse.

Multisensory detection of drying monitoring in the electrode production

Dirk Hofmann

Fraunhofer Institute for Ceramic Technologies and Systems IKTS

In the manufacture of lithium-ion batteries, electrode production is a decisive factor for the subsequent performance of the cell. Early detection of defects or changed material properties can significantly increase the quality of electrode and therefore the whole process. The test medium continuously changes its coherence and consistency during each process step and thus its fundamental material properties.

The following article describes the process of drying monitoring using a multi-sensor system. The aim is to monitor the state of the percolation, which is divided into several areas. A deci-sive step is the homogeneous formation of the electrode morphology, whereby an electrically conductive film structure is created. The respective properties to be detected can be monitored by different physical principles.

The paper presents a multisensor setup consisting of a near-infrared sensor, a distance sen-sor, a temperature sensor and an eddy current sensor. In addition to the pure process proper-ties, product and material parameters, such as the conductive and non-conductive properties, which qualitatively characterize the later cell, can be determined. The focus of this investiga-tion is finally the correlation and combination of the individual properties and the subsequent transfer to the production line.

Material development and production

Impact of spheroidization of natural graphite on fast-charging capability of anodes for LIB

Steffen Fischer[1], Stefan Doose[1,2], Jannes Müller[1,2], Christian Höfels[3], Arno Kwade[1,2]

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Despite numerous research on new active materials for anodes, graphite is still the most common material used in Li-ion batteries. For application in electric vehicles and especially fast-charging, a spherical shape has proven to be beneficial. So far, the spheroidization of natural flake graphite is conducted by a rigid and lavish cascade process.

In this work, a scalable classifier mill was used for spheroidization. It was demonstrated that a spheroidization time of 15 minutes is sufficient to improve material properties and enhances electrochemical performance, while maintaining high process yields of 55 %. Higher spheroidization times decreased the process yield and showed only slight changes in particle morphology, but did not improve the overall electrochemical performance. This process provides the possibility of large-scale spheroidization of graphite with short stress duration times and also enhanced cycle stability and rate capability. Insights into the influence of the morphology on the intrinsic and structural properties of the graphite particles and manufactured electrodes are provided. Spheroidization creates new pores in the coating layer, while reduces the electrical conductivity by 1.2 and increases the surface area of the graphite particles by a factor of 1.8. We demonstrate that the spherical shape improves the adhesion strength and long-term cycle stability by a factor of 2.2 and 1.3, respectively, as well as the discharge rate capability by 1.8. The specific charge capacity could be enhanced by a factor of 2.3 at a C-rate of 3. With an additional carbon-coating, the specific surface area could be significantly decreased and the specific capacity at high C-rates further increased. In comparison to a commercial available graphite, the manufactured and refined graphite retains 90 % of the capacity after 200 cycles.

New styrene-butadiene rubber (SBR) binder for SiOx anode in lithium ion battery (LIB).

Shoudai Kurosumi
ENEOS Materials Belgium

The development toward LIB with high energy density is drawing a strong attention from the battery and car manufactures because it can significantly contribute to extend the cruising distance of electric vehicles (EV). Among various approaches to achieve high energy density, SiOx anode is one of the most promising candidates for next generation LIB thanks to its high theoretical capacity.

However, SiOx anode has two main issues to be solved for practical use:

1.Expansion and shrinkage of SiOx particles during charge and discharge cycles leads to the loss of the electrical conductive path and large deterioration of the anode capacity. As a result, the cycle performance that is the indicator of battery life is deteriorated.

2. Degassing during cell storage at high temperature causes the swell and burst of the cell. These phenomena give bad influence on the battery life and the safety property.

For issue 1, we have developed SBR binders with a strong adhesion to SiOx particles by controlling its modulus precisely. The optimized binders could suppress shrinkage and swelling of SiOx electrode leading to the extension of battery life.

About issue 2, in order to investigate the mechanism of gas evolution, the analysis by gas chromatography was performed.

Based on the examinations for issue 1 and 2, we developed new binder with precisely controlled property at particle surface and functional group to solve both problems. SiOx anode with this binder showed 70% better cycle performance than that of conventional SBR and suppressed electrode expansion thanks to its high elastic modulus. Moreover, the suppression of gas evolution was observed by our binders partially melted morphology in the electrode and its high coverage of active materials.

We expect that our new SBR binder can contribute to commercialize SiOx anode with good cycle performance and high safety.

Investigation of particulate properties and carbon coating on high-capacity nano-silicon graphite composites

Jannes Müller
TU Braunschweig | Institute for Particle Technolgy (iPAT)

Silicon is considered the most promising material for (partially) replacing graphite on the anode side of lithium-ion batteries, because of its high abundance, low costs and high specific capacity. However, the low electrical conductivity and severe volume expansion upon lithiation, which leads to high stress on the electrode structure, hinder the industrial usage. Therefore, the influence of particulate properties on performance and the design of new structures, which can be produced at a high level of scale, is important.

In this study, a core-shell structured nano-silicon graphite composite (Si@Gr, 8 wt.% silicon, 600 mAh g 1) was manufactured by fluidized bed granulation and the influence of particle size, silicon content and a carbon coating were studied in more detail. It could be shown, that a smaller silicon particle size as well as a smaller silicon content led to improved electrochemical performance. One major factor for this is the poor stability of composite particles, which could be detected via particle size measurements while applying ultrasonic stress, and the greater volume expansion of the electrodes. Furthermore, a detailed calendering study emphasized the importance of electrode density, as at higher densities, which is equivalent to lower electrode porosity, the electrochemical performance clearly deteriorated. A pitch derived carbon coating on the composite (Si@Gr/C) enabled an improved electrochemical performance (pristine electrodes: 90 % capacity retention after 125 cycles compared to the uncoated composite) even at the highest electrode density. In conclusion, this study elucidated the influence of various particulate properties and helped to optimize the performance of silicon containing composites.

Rheological behavior of high Ni cathode materials function of PVDF nature

Gregory and Cyrille Schmidt and Mathieu
ARKEMA

The high energy density demand requests the use of high Ni cathode materials with very high pH and electrode loading increase. One drawback is the limited slurry stability with time of some PVDF binders. Thanks to appropriated rheological measurement (G', G'' and Tan Delta), the mechanism of this slurry instability have been studied. We will show that the slurry instability is clearly linked to 1- NMC morphology and nature and 2- PVDF structure. By playing on the PVDF formulation and additivation, we can monitor the slurry stability as well as the electrode properties like peeling strength and electrochemical performances.

Revealing the rate-limiting electrode for full cell with high mass loading and C rates

Dimitra Spathara & Yongxiu Chen
University of Birmingham

Lithium-ion batteries with superior capacities and rate performance are needed due to the soaring demands for higher energy and power device requirements. However, the main hurdle on achieving this predominately results from the poor rate performance of electrode, which is related to thermodynamic limitations and slow kinetics. To determine the rate-limiting electrode in NMC622 vs graphite cells, a methodology based upon the galvanic intermittent titration technique, for investigating the diffusion and reaction kinetics from the observed overpotential at each electrode has been developed. Variable current densities have been used to simultaneously extract the thermodynamic and kinetic properties of each electrode with increasing mass loading. Graphite is observed to reach its thermodynamic limits quicker than NMC, due to the flat plateaus and overpotentials observed from the charge transfer kinetics and mass transport. At high rates and high mass loadings, the graphite electrode is responsible for limiting both Li+ diffusion and reaction rates in full cells. Slow diffusion kinetics are caused by the transport of the electrolyte in the porous electrode, which limits the availability of Li+ for reaction at the surface of graphite. This methodology is proposed as a fast single technique for comprehensively parameterizing the rate limitations observed in a full cell configuration.

Tailored polysaccharide binders for aqueous processing of Ni-rich layered oxides cathodes

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University of Münster, Münster Electrochemical Energy Technology (MEET)

Lithium ion batteries (LIBs) are a vital enabler for sustainable energy storage and mobility. To ensure extensive market penetration of electric vehicles, there is a strong interest to further reduce the environmental impact and costs of the electrode manufacturing process. In this sense, the aqueous processing of the LIB cathode electrodes has become a strong focus of interest to enable the removal of the state-of-the-art teratogenic N-Methyl-2-pyrrolidone (NMP) solvent and the fluorinated polymer polyvinylidene difluoride (PVDF) binder [1]. Due to the elimination of the recovery step when using de-ionized water as solvent, up to 2 % of production costs and up to 3-6 million $ of capital investments can be saved [2]. Furthermore, the recycling process of water-soluble binders is less expensive, which means that the production scrap of the cell assembly (around 28 %) can be reused and additionally lower the overall battery production cost [3]. This work focuses on the investigation of tailormade polysaccharides as binders for the cathode electrode processing due to their water-solubility, low costs, sustainability and high functionality. Besides sodium carboxymethyl cellulose (Na-CMC), which is a commonly used binder in LIBs anodes, there are many more different available polysaccharides with unique properties that can be suitable for the aqueous processing of the cathode. Herein, different polysaccharide binders are thoroughly characterized and compared in terms of their thermal and high voltage stability, production feasibility (viscosity and adhesion on carbon-coated aluminum foil current collector) and electrochemical performance in LIB cells using Ni-rich layered oxide cathode materials.

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Multi-scale modeling of Structural Li-ion Batteries

David Rollin

TU Braunschweig | Institute of Applied Mechanics (IAM)

Structural Li-ion Batteries represent one possible route to overcome limitations of conventional battery designs regarding their limited energy storage to weight ratio: Besides their energy storage functionality they are also able to sustain mechanical loads. In Structural Li-ion Batteries, the electrodes consist of carbon fibers embedded in a porous polymer matrix, which is filled with an electrolyte. In the positive electrode, the lithium storing material is provided by a coating on the fibers. The resulting multi-functional composite material can be utilized as energy storage.

Further applications are possible in electro-chemical actuators, in structural energy harvesting, and strain sensing devices. The bi-functionality of such devices is conveyed by various multi-physics interactions being observed at multiple length. These include intercalation of Li-ions and subsequent swelling of electrode material, reaction kinetics at material interfaces, thermal effects and many more.

We present a computational framework which will help describe and understand those multi-physics interactions in a virtual lab with the aim to assist battery development and design. For this purpose, the electro-chemo-thermo-mechanically coupled problem is modeled from the sub-micron to the cm scale utilizing the Finite Element Method combined with scale-bridging approaches.

Understanding the Influences of Laser Perforation on Thick Electrodes for Lithium Ion Batteries via 3D Microstructure Simulations

Lukas Krumbein

German Aerospace Center (DLR), Institute of Engineering Thermodynamics

Laser perforation is a precise technique to decrease ionic diffusion limitations by selectively removing material with spatial precisions of tenth of micrometres. It is mainly applied in thick electrodes to improve foremost rate capability, as well as cycle stability, Li plating detention and wetting efficiency. [1] [2]

Mostly, holes are created in the batteries through direction leading to a material removal of about 5%-10% of the initial load. This removal creates inhomogeneous diffusion channels especially into layers close to the current collector, as opposed to a homogeneous increase in porosity.

It is of interest to find an optimal trade-off between the competing factors of capacity loss and increase in ion conductivity due to material ablation. Optimization of structuring parameters requires intimate knowledge of electrode and material properties. However, there is a lack of an adequate description of the inhomogeneous structure and its influence on the electrochemical performance.[1]

In our presentation we show a detailed 3D microstructure resolved simulation study, examining the influencing parameters for laser perforation.

The data suggests, that perforating holes with small diameter at a short distance, which results in an ablation of ca. 8% gives generally desirable improvements for the rate capability. Laser perforation is distinctively favourable in contrast to a raise in homogenous porosity.

Moreover, the microstructure resolved simulation also allows for a detailed analysis of different hole shapes and hole misalignment in electrodes after stacking. We evaluate the impact of different configurations on the electro chemical performance. [3]

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Establishment and application of lithium metal anodes on novel metal-polymer composite current collectors to increase safety and energy density

Julian Brokmann, Nikolas Dilger, Matteo Kaminski, Jutta Hesselbach, Sabrina Zellmer, Arno Kwade

Fraunhofer Institute for Surface Engineering and Thin Films IST

The electrification of mobility is one of the main drivers of the increasing demand for batteries, this calls for high gravimetric and volumetric energy densities (ED) of batteries. The use of solid electrolytes (SE) in all-solid-state batteries (ASSB) enables improved ED, operational reliability, shelf life and C-rates by replacing the inflammable liquid electrolyte. Additionally, the employment of SE enables the utilization of e.g. metallic lithium anodes. To achieve an increasement of energy density, which, however, goes hand in hand with challenges in complying with safety guidelines is a key requirement in the field of ASSB. Therefore, it is important to develop innovative technologies that improve the safety of current and next-generation LIBs while taking ecological and economic aspects into account and, at best, contribute directly to an increase in energy density.

A decisive factor for increasing the energy density and the operational safety is the use of new types of current conductors. For this purpose, in this work, metallized polymer films are used as current collectors, which are lighter than conventional metal films due to their lower density. The aim of the work is to produce lithium metal anodes on metal-polymer composite current collectors provided by the project partner. Via a systematic investigation of the process parameters for the production of thin lithium coatings on the composite collectors and conventional copper foil as reference material. A physical vapor deposition process, magnetron sputtering, is used for coating with lithium. Subsequently, working windows for the production of the anodes for the use of the different collector materials will be derived. To produce qualifiable results, the anodes with the best mechanical and chemical properties are installed in full cells and tested for their electrochemical properties. In the final phase, recommendations for the use of metal-polymer composite current collectors in solid-state batteries will be made from the resulting results and adapted to new cell chemistries.

POSTER ABSTRACTS I Day 2

Cell assembly

Performance of ultrasonic-welded contacts of metallized polymer foils with insertion of conductive additives

Hakon Gruhn
TU Braunschweig | Institute of Joining and Welding (ifs)

Increasing demands regarding battery performance and safety call for new materials. This is not just limited to active materials . The current collectors almost exclusively are made from copper for anode and aluminum for cathode. However, newest research focus on metallized polymer foils as current collector material. These materials can avoid thermal runaways caused by internal short circuits. As a consequence, production steps in cell manufacturing must be adapted. Especially the contacting is challenging due to the insulating polymer layer. While sufficient mechanical strength is reached by ultrasonic welding, the electrical conductivity is limited. Therefore, in this work conductive materials as aluminum foil, tin solder or carbon fibers are placed between the foils to be welded to enhance electrical conductivity and to prevent a bottleneck in form of Joule heating. Subsequently, specimens were welded and characterized by lap shear tests and 4-point probe measurements. The results show significant differences in the electrical resistance by adding the highly conductive materials between the plies before welding.

Flexibility and high throughput for the battery cell stack formation – A new machine concept

Sebastian Henschel
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Over the past years, the demand for lithium-ion-batteries has not only increased significantly, but also began diversifying in terms of cell dimensions and applications. It is therefore necessary for the industry to offer new manufacturing solutions, which provide for a flexible cell manufacturing, while at the same time enabling a high throughput in order to ensure economic feasibility. This work presents a new approach for a flexible cell stack formation, which combines the usually separated process steps of cutting and stacking electrode sheets. By doing so the high throughput, normally found in the production of cylindrical cells can be combined with the flexibility of a stacked pouch cell. The resulting machine is designed to offer a greater flexibility than any other machine on the market in regard to the manufactured electrode sizes and at the same time is calculated to reach state of the art stacking speeds. The electrodes dimensions can be adjusted in a matter of minutes using software commands, without having to undergo time consuming manual alignment and adjustment processes.

Development and Usage of Digital Twins to Optimize Battery Cell Stacking Processes and Machinery

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In addition to the significantly increasing demand for battery cells, other observable trends, such as the increasing variety of materials and the desire for format flexibility, present enormous challenges for the respective production processes and machines. This applies to the phases of development, ramp-up and operation of new production processes and machines. These phases are often not coordinated with one another in the context of the observable trends. The use of digital twins in the three phases offers the potential to optimize the development of production systems and their application. In this work, the development and use of a continuously evolving digital twin for the phases of machine development, ramp-up and operation is presented using the example of flexible cell stack formation. For the development phase, the digital twin is used to test and validate the machine concept. In the ramp-up phase, the digital twin is used to determine the optimal setting parameters for different production specifications. The use of the digital twin during operation aims at the real-time virtual sensing of non-measurable parameters based on real input data.

Mini-Environments as an enabler for an economical and ecological battery cell production

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The demand for more powerful batteries has increased rapidly over the years. In particular, the automotive industry relies on lithium-ion battery technology [1]. One goal is to increase the range of vehicles to convince consumers to use electrified mobility. To fulfill the demand for higher gravimetric and volumetric energy density of LIB, the cell chemistry and composition are changing towards nickel-rich lithium-ion or lithium- metal batteries [2,3]. Since these materials are significantly more sensitive to moisture, the production conditions need to be adapted accordingly [4].
Therefore, Mini-Environments (ME) can be a solution to reduce the costs and energy required for a dry production environment. The sealed containment encloses the production plants close to the process. Compared to the conventional drying rooms the space capacity is reduced. ME are already established in other industries (e.g. semiconductor production). However, it cannot cover the requirements needed in battery production. The implementation for moisture management at low dew point temperatures is not yet fully developed. Therefore, the transformation to battery cell production is looking prospective.
To establish the ME concept in battery cell production, the following measures must be implemented:
- Identification and analysis of the parameters influencing the process technology
- Investigation of effortless and safe insertion and removal of battery cells
- Clustering of processes for more sustainability
- Identification of costs saving potentials in comparison to conventional drying rooms

In this contribution, first solutions and approaches to address measures regarding process development and plant integration are presented. The cluster model illustrates a demand-driven process environment. The concept design of the ME is completed in the cylinder cell's production line.

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Project "QuaLiZell": Failure Mode and Effects Analysis of Critical Safety Aspects in Lithium-ion Cell Production

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This talk will give an overall introduction on the project “QuaLiZell”. QuaLiZell belongs to the competence cluster – Aqua, which is funded by Federal ministry of Education and Research of Germany (BMBF).
The QuaLiZell project is dedicated on quality assurance and failure analysis in the process of lithium-ion pouch cells assembly. The analysis focuses on processing errors and material defects that can occur during the cutting and stacking process of separators and electrodes. The aim of this project is to identify safety-relevant sources of defects in the production steps, to clarify the cause-and-effect relationships, to quantify the tolerance and intervention limits and to develop suitable analytical in-line methods for the real-time detection of production failures.
First, identifications of various errors are defined, which include cutting quality of the electrode and separator edges, stacking accuracy of the individual sheets and contamination from foreign particles. Their potential failure causes are identified and evaluated with respect to their probability of occurrence. Second, pouch cells are assembled with specifically introduced cell defects. The cells are compared with reference cells by means of electrochemical analyses (including cycling, rate tests, and de-

termination of internal resistance) and post-mortem investigations. Last but not least, an end-of-line test for an early detection of critical cells is being developed.
The results obtained to date provide a first step towards quality assurance and allow initial conclusions to be drawn regarding tolerance and intervention limits in the regarding processes.

Fast Cell-Internal Contacting of Large Foil Stacks Using Micro Friction Stir Spot Welding

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The fast production of high-performing lithium-ion batteries still poses a challenge in battery production. One bottle neck is the process of cell-internal contacting, during which the electrode foils of the anode and the cathode are joined with the arrester tab. The joints are usually fabricated using ultrasonic or laser beam welding, however, both joining processes show a limited performance when it comes to the fast and high-quality welding of large foil stacks. On this poster, a different approach for cell-internal contacting is presented. The theoretical and experimental studies conducted proved that with micro friction stir spot welding (µFSSW), large stacks consisting of 100 electrode sheets can be joined in only a few tenths of a second and with a high quality. µFSSW therefore has a high application potential for cell-internal contacting, especially for large stacks.

Cell Types, module and pack design and production

3D-Printed Cell Housings for Acadamic Battery Research

Paul-Martin Luc
Technische Universität Berlin

Coin (type 2032) and Swagelok cells are commonly used in lithium-ion battery (LIB) research and development. Based on the simple structure and the possibility of manual production, both cells types enable quick examinations compared to larger cell formats. Due to the small size and the relatively large ratio of inactive (housing) to active cell components (electrodes, separator and electrolyte) of these cells, the quality of the experimental data is rather qualitative. Above all, the scalability from 3mAh to 50Ah cells is rather questionable. In order to be more variable in the design and size of the cell format and also to reduce the costs of cell components, the use of additive manufacturing (3D-printing, stereolithography) for cell housings was investigated. In an iterative design process, various printing materials (resins) as well as the pressure on the cell compound were modified and tested. To quantify the reproducibility of the cell performance, parameters of at least nine cells were determined and compared to other cell types like coin cells, Swagelok cells and the EL-Cell.
Accordingly, cell housing additively manufactured using stereolithography are not yet as reproducible as conventional cell housings mentioned above. Advantages of 3D-printed cell housings such as reusability, reduced costs, better scalability and less space required in a glovebox do not compensate for the disadvantages such as the printing process with the waste produced and the rapid decline in the discharge capacity. More chemical resistant resins and coatings needs to be investigated.

Iterative approach for comprehensive optimization of product life cycle by interconnecting packaging and thermal modeling of battery cells

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Electromobility is booming - fossil fuels are expected to be replaced by renewable energies in the long term. The necessary traction energy is provided by lithium-ion batteries.
The Model2Life project, funded by the Federal Ministry of Education and Research, rethinks the interface from automotive applications in First Life to stationary applications in Second Life to enhance overall product lifecycle sustainability. The framework for the overall system optimization is a system model, which combines domain-specific individual models. Model-Based-Systems-Engineering (MBSE) is used to methodically build up a digital twin of the battery. A sub-area of the system model is an innovative combination of the domains installation space and electro-thermal modeling.
The unique feature in the project design is the iterative approach, which evaluates a first basic calculation of the design space fitting and optimizations based on a thermal single cell simulation. The design space model performs an optimization of the battery cell layout on module and pack level. The requirements from the first as well as the second application are considered to enhance product lifetime. For the thermal validation of the battery model, the automatically created layout is transferred to an electrothermal simulation approach. In this simulation static and dynamic loads are computed to evaluate compliance with safe operating limits.
In a subsequent feedback loop, the solution space between the design model and a detailed thermal Multiphysics simulation is narrowed down and optimized. The result is a battery system optimized for the overall life cycle.

Evaluation and Comparison of Requirements and LIB-Technologies for Electrified Mobile and Stationary Applications

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Lithium-ion batteries (LIBs) are currently the most attractive energy storage technology owing to their unique properties including the high energy density and high power density, reinforced by a long cycle life and the high energy efficiency. The rapid development of the LIB-technology is focused on the successfully establishment of the electric vehicles (EVs) in the mass consumer market. A significant improvement of suitable active materials and manufacturing technologies led in recent years to a wide variety of LIBs with different cell chemistries, high rate capability, lifetime and safety associated with low production costs [1].
Currently, also the electrification of other large mobile applications such as passenger ferries, short-distance trains and trucks for heavy transport [2], as well as the generation and storage of renewable energies by stationary storage applications [3] open up new markets for the use of LIBs and presenting the LIB-technology with new challenges. LIB-manufacturers have reacted to market demand and are already offering large-format LIBs with a wide performance profile.
This study presents a database of over 1000 different commercially available LIBs from reputable LIB-manufacturers. The database contains LIBs with the cell chemistries based on the cathode active materials LFP, NMC, NCA, NMC/LFP and based on the anode active materials graphite and LTO. Furthermore, the cell housing is considered separately and starting with cylindrical cells of the 18650- und 21700-format, reach prismatic LIBs a nominal capacity up to 400 Ah. The evaluation of the LIB-properties in terms of volume, weight, specific energy, energy density, specific power and power density is applied to compare the commercially available LIB-technologies. A novel method for the investigation of the suitability of LIBs for various electrified mobile and stationary applications is presented.

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Influence of the cell dimensions on electrochemical cell properties

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Driven by the demand for mobile energy storage, the production of lithium-ion batteries with high flexibility in quantity and moreover in the cell dimensions is currently a key challenge for a sustainable energy usage. However, profound studies of the influence of the cell dimensions on the electrochemical behaviour of lithium-ion batteries are still inaccessible.

In our work, we show performance data on self-assembled trapezoidal pouch type cells compared to their rectangular equivalents. Both cell formats show almost identical cycling stability of around 4000 cycles before reaching 80 % of the initial capacity. These results are comparable to industrial cells. Furthermore, they feature similar rate capability but different inner resistances, which is based on the electrode area.

Further, we will present the concept of planed more expanded studies on the dimension-property relationships. This includes not only electrochemical characterizations and cell cycling but also non-contact electric current measurements on rare but promising space-filling formats like L-, pyramid- and donut-shaped pouch cells. To realize up to 6 mm stack hight, a major focus lies on the flexible production of differently shaped deep-drawn pouch foils which embed the cell stacks.

The research is partially embedded in the Battery2020 project PaXibel which complements the InZePro-Cluster project AgiloBat2 with a deep-drawing tool that provides access to individually shaped, deep-drawn pouch foils.

Lithium-ion cell format and geometry optimization based on system integration capability and requirements for electric vehicles

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In order to fulfill the Paris climate agreement, electrically powered vehicles are considered to play a decisive role in future mobility. However, the development of electric vehicles (EVs) is associated with numerous new challenges to simultaneously increase EV performance, ensure longevity, and reduce overall costs. As the most expensive component of the overall battery system, the lithium-ion battery cell offers extensive optimization potential. To investigate this potential, this work contributes cost-sensitive system integration optimizations for different cell formats, sizes, and chemistries based on various EV battery requirements. In addition to pure cell-specific properties like energy density, cell voltage, or mechanical stiffness, particularly the system integration capability for different cells is observed. A novel cell geometry optimization is performed using a generic multi-physical battery system optimization tool. Thereby, individual simulation models which represent the battery system's main component groups of cellmodule, cooling, mechanics, and electronics are interactively coupled. Thus, the integration capability of the observed cell geometries is evaluated from cell to module to system level. An optimization is performed using a combined algorithm from the field of Gaussian process regression and classification. Trade-off balancing between different cost aspects of multiple system-related components is exemplarily depicted to stress the importance of optimized cell geometry usage. Moreover, analyses with different EV requirements indicate the indispensability of various different cell sizes.

Formation and aging

Physico-chemical modeling approach to analyze fast charging strategies and aging

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Fast charging is one of the key requirements for lithium-ion batteries in automotive applications and designing and developing suitable battery cells and charging protocols is therefore an important factor for the success of electric vehicles [1]. In this work a physico-chemical modeling approach to analyze fast charging strategies and aging for lithium-ion batteries is proposed. The model is based on the common Doyle-Fuller-Newman approach, which is extended with a surface reaction model for lithium plating [2]. The later covers lithium plating as well as stripping as a side reaction to intercalation and also is capable to distinguish between reversible and irreversible plating. This approach allows to evaluate different fast charging strategies under plating conditions with reduced computational time. The model can be amended with more complex surface reactions to account for additional degradation processes in future work.

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Cell-Internal Glass Fiber Sensors for In-situ Temperature Monitoring in LIB

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Lithium-ion batteries (LIB), featuring high energy density and power density, can be found in various fields of application. One of the most important requirements for their application is to ensure their safety and continuous performance under different operating conditions. To ensure the afore mentioned factors, in-situ monitoring of internal cell parameters, such as temperature, state-of-charge, and state-of-health of LIB is essential. The cell temperature is a crucial factor for both safety and LIB's health. Not only the average temperature but also the temperature distribution inside the cell must be considered. However, common battery management systems mostly rely on monitoring the surface temperature of the cells, while neglecting changes of the internal parameters. This is where our work will make a significant contribution.

The integration of glass fiber sensors into battery cells, allowing direct monitoring of internal temperature changes during operation, will be presented. We will focus on different approaches for the integration of glass fiber sensors and on their influence on the performance of the LIB. Finally, we will present the use of glass fiber sensors for in-situ temperature measurements inside of LIB cells, which will improve the safety and performance of LIBs.

Data Mining-based Aging Diagnosis of Lithium-Ion Batteries

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Rechargeable batteries play a key role in the electrification and hence de-carbonization of our society. Today, Lithium-ion batteries represent the leading battery technology, as they exhibit a number of highly promising properties, such as high energy and power density, and a long cycle life, which make their use in portable and mobile applications particularly amenable. The performance of a battery cell is strongly dependent on cell chemistry and cell design as well as on its load profile, application and environmental conditions. Moreover, during operation and even in rest conditions, the complex interplay between varying electrochemical processes occurring inside the cell causes aging of the battery, which leads to an irreversible loss of capacity and finally to failure of the battery cell.

In order to undertake a comprehensive aging analysis, which allows for clear identification of specific degradation processes, in this work, a number of different measurement techniques were carried out, such as cyclic aging tests, electrochemical impedance spectroscopy, and optical sensor measurements. Subsequently, the generated data were analyzed using incremental capacity analysis, differential voltage analysis, and the distribution of relaxation times, where representative aging features showing a clear correlation to specific degradation processes were extracted from the corresponding spectra.

Based on these results an aging matrix was created linking three major aging processes, namely loss of active material, loss of lithium inventory, and conductivity loss, to characteristic features in the spectra. One major aging process may contain various aging phenomena for different cells, for example, lithium plating, SEI formation and particle cracking as part of loss of lithium inventory, Binder decomposition and current collector corrosion as part of conductivity loss, electrode decomposition and transition metal dissolution as part of loss of active material. However, the identification and quantification of those detailed aging phenomena is still a such huge challenge. In this work, only those major aging processes were concerned, identifying the effects of different degradation modes inside the battery and finding the corresponding aging data features would be the main purpose.

Through the accomplishment of this aging data features and battery aging matrix, those features extracted from different analysis methods were compared with each other, and the most suitable analysis methods for the corresponding aging processes were selected. The aging values of the major aging processes can be calculated through the extracted features based on the aging equations, and the parameter results obtained from the equivalent circuit model were also utilized to validate those aging quantification results.

Since manual extraction of that large amount of features is rather cost and time consuming from large amount of aging data, a digital workflow containing all data processing steps required for automatized feature identification and selection was established and implemented into a battery database. Data mining techniques have been widely used in recent research and industry for big data information and knowledge acquisition, data description, and summarization. In this work, data mining techniques were employed in order to assign those features to a specific aging process, such as clustering and classification techniques, thus allowing for a fast and targeted aging diagnosis of the battery cell under investigation.

Development of fast charging strategies for lithium-ion battery cells using an electro-thermal model approach

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Fast charging of lithium-ion batteries is a decisive criterion for the acceptance of electromobility in society. The requirements for fast charging differ depending on the application, which is often limited by the material system and cell design. In the aging process, the cell properties degrade, which can be accelerated by fast charging cycles. Therefore, the operating limits are often configured pessimistically, in order to avoid accelerated aging effects and safety-critical processes. Another possibility is to determine the aging-dependent operating limits and to adapt the charging strategy accordingly. Three-electrode cell setups enable to measure the positive and negative electrode voltage severally, so that electrical equivalent circuit models (EECM) can be parameterized for each electrode separately. Consequently, fast charging profiles can be simulated by pretending a minimum anode voltage. The safety-critical deposition of metallic lithium (lithium-plating) occurs with a negative anode voltage and can lead to irreversible loss of lithium ions. In automotive applications, larger cell formats are needed. Scaling up the simulated charging strategy based on three-electrode cells to larger pouch cell formats poses a challenge. The stainless steel plunger used in the three-electrode cell setup have relative large heat capacities compared to the heat generation of the coin cells, so that constant temperatures in the coin cells are expected during the charging process. In the pouch cell format can be noticed a variation of temperature along two dimensions (length and breadth) which leads to higher ohmic resistances in colder areas of the cell. In these areas, the probability of lithium-plating increases. In order to avoid this, the EECM is coupled with a thermal equivalent circuit model. As a result, the temperature distribution of the pouch cells can be involved in the development of new charging strategies through temperature-dependent parameterization of the EECM. The area of the cell which has the highest resistance due to temperature limits the charging current of the charging profile.

Effects of mechanical pressure on pouch-cell performance during formation and cycling

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One cause of reduced lithium-ion diffusion is the development of gases within the lithium ion cell, which form during formation but also during operation. Gas developments reduce cell performance and can lead to irreversible expansion. A promising approach to detect and investigate such gas developments is to measure the internal pressure of lithium-ion cells and study the resulting pressure profile during formation and cycling. By specifically investigating the internal pressure distribution and the expansion of lithium-ion cells, measurement data are generated. This allows conclusions about electrochemical processes within the cell as well as cause-effect relationships and causes of gas formation. One approach is to brace the cells under external pressure, which forces the gas out of the electrode interlayers. In addition, contact losses can be reduced and ion diffusion is to be improved. These advantages are offset by a reduced diffusion capacity due to a reduction in material porosity when the pressure is too high.
The experimental investigations are carried out using pouch cells that are clamped in a product carrier. The applied pressure range is up to 350 kPa. The internal pressure distribution of the lithium-ion cell is determined using a pressure measuring foil. With the pressure measuring foils, the pressure profile of the lithium-ion batteries can be measured dynamically during formation and cycling. This means that the times when the internal pressure developed and peaks of the internal pressure can be determined.

Optical and chemical characterization of defects in pouch cells caused by local pressure

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Pouch cells are intentionally compressed during their operation. The optimal degree of compression for a prolonged lifetime is still to be exactly defined. During the lifetime of battery cells their thickness increase during charging (reversible) and cycling (irreversible). The increase in thickness is causing compression changes when compared to the initial compression. Compression changes are hardly predictable in amount and locality. Unappropriated pressure can induce certain degradation mechanisms inside the battery cell and accelerate its aging.
Here we pressed the pouch cells locally during cyling to produce local defects. Further we evaluate two techniques to locate and identify such defects: A non-destructive technique: Scanning acoustic microscopy (SAM) and a post-mortem analysis: Raman spectroscopy. In this way we can investigate how the pressure influences degradation mechanisms of pouch cells. SAM is used to localize inhomogeneities along the surface of the electrodes without opening the battery cell. Raman spectroscopy was used to map the areal distribution of degradation products on the surface of the electrodes.
Commercially available NMC pouch cells were used in this evaluation study.

Effects of electrochemical impedance spectroscopy before and during formation

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The formation of lithium-ion batteries is an important and time-consuming process step in battery production. Good formation can positively influence cell properties and save process time.
A central aspect of the investigations is the experimental integration of electrochemical impedance spectroscopy (EIS) before and during formation. A critical aspect of this measurement methodology is the feedback effects of the EIS measurements on the battery cells being formed. Current excitation during the measurement may already partially form the battery cells. Therefore, it will also be analyzed if and how the performance of the battery cells is changed by early impedance measurements. For this purpose, capacitance tests, internal resistance tests and post-mortem analyses will be performed on the battery cells. With the help of the knowledge gained here about the methodology, the metrological analysis of battery cells should already be possible during the formation process. Special three-electrode cells are used for these investigations.

Options for fiber optic sensors on lithium-ion cells for prognostic health management under harsh conditions

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Lithium-ion battery cells are the energy storage solution of choice in modern applications. The increasing development of compact high-energy battery systems for electric vehicles continues to require well-designed monitoring and control methods. Especially, the inaccessibility of intracellular state variables poses a challenge for the prognostic health management of a battery system. This hinders efforts for lifelong optimized operation, safety and maintenance. As these are critical aspects of any battery system, many heuristic approaches are regularly published, which rely upon sophisticated models as well as ambient conditions, current, cell voltage and outer cell temperature trying to provide a solution.
In this work, an alternative is presented. Employing robust and cheap fibre optical sensors across the surface of pouch cells enables the direct measurement of the spatial distribution of cell temperatures and strain of the pouch material with high resolution. These new options provide a significant addition to the existing possibilities for the assessment of cell state degradation. For testing the capabilities of this approach, several pouch cells at their beginning of life are equipped with fibre optical sensors and then cycled under harsh conditions promoting the variance of the aging progression. After the cycling, the resulting degradation effects are analyzed with respect to the various sensor positions.

Thereby, the most insightful measurable quantities for each cycling condition are identified. The results from this work enable the evaluation of sensor redundancy and open the discussion of optimal sensor positioning.

Production of next-generation batteries

Development of a Lithium-ion battery digital twin

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Lithium-ion batteries are widely used in various applications because of their favourable properties, including high energy density, low memory effect, and low self-discharge rate. However, further research is needed to enhance the performance of lithium-ion batteries to their full potential. Experiments are the most reliable method for investigating battery behaviour. However, these methods are time-consuming and expensive and cannot meet the rapidly growing industrial needs. To reduce the experimental effort, various battery modelling methods have been used for simulating lithium-ion battery behaviour and internal processes. During a battery's lifespan, operating and environmental conditions influence its performance, so model parameters must be constantly updated. Data from battery lifetime is required for this parameter estimation. However, generating this data will be labour-intensive and expensive and will require many hours of cycling tests. To solve this problem, Machine Learning (ML) algorithms can be used to generate data on the entire battery lifetime based on data from a specific period of a battery's life. Therefore, a fusion of physics-based models, ML algorithms, and data can be used to create a Digital Twin (DT) for batteries to reduce the need for experiments. With this tool, experiments can be performed in a digital environment in a significantly shorter amount of time; therefore, theories and design ideas can be expedited, contributing to the faster development of lithium-ion batteries.

Novel binders and additives for Zinc anodes in Zinc-Air Batteries

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Secondary Metal-Air batteries have the potential to become a high capacity, safe and environmentally friendly alternative to Lithium-Ion batteries. Zinc-Air batteries (ZABs) are the most mature and nearest to being commercialized.1 The intrinsic safety characteristics of systems using aqueous electrolytes, the high theoretical specific energy of ZABs and the natural abundance as well as the environmentally friendly nature of the active material make this a very attractive technology. Primary ZABs have long been successfully sold for niche applications such as hearing aids. However, their use as secondary batteries is hampered by several factors, including anodic passivation by Zinc oxide formation and dendrite formation during charging.2 Our research and results being presented here address these issues.

Here we report on the use of novel binders and ion-exchange additives for the preparation of slurries that also contain Zinc particles and carbon black. These slurries are coated onto copper meshes and cycled in a three-electrode-setup in cells with either stagnant or flowing electrolyte. After an initial discharge the cells are either charged using a continuous or pulsed sequence.

The performance of the ZABs is shown to be dependent on the nature and the amount of the ion-exchange resin added to the anode slurry. A modest amount of a sulfonic acid decorated resin result in a much greater capacity being accessible during the initial discharging of the cell. We are also able to show, that the substitution of the reference PVdF binder by either Polyurethane or Nitril-Butyl-Rubber binders result in better discharge behavior.

Clearly, the components of the anode have an influence on the performance of ZABs. The possible coordination of the generated Zincate ions by the functional groups of the ion-exchange resins or the nitrogen atoms in the binder polymers might well explain the observed improvements in the performance of the ZABs. For comparison, the use of surfactants and soluble polymers3 as electrolyte additives are shown to have a positive effect on the electrochemistry of ZABs.

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Densification of Li3PS4-based separators for all-solid-state batteries by uniaxial pressing

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All-solid-state batteries are promising for the next generation of lithium-ion batteries. The replacement of the liquid electrolyte with a solid material can improve the power density, as well as the battery safety. For this purpose, sulfides are one particularly interesting candidate, as they have the highest ionic conductivities of all solid electrolytes. The process chain for sulfide-based all-solid-sate batteries somewhat resembles that of lithium-ion batteries and promising first results have been obtained on a lab-scale. As the ionic transport within the separator takes place via the solid structure a reduction of the porosity and good particle contacts are key to a sufficient ionic conductivity. Hence, one important process step is the densification of sulfide-based separators. In literature, separators are often compressed by uniaxial pressing but detailed studies on the impact of temperature and pressure with respect to sheet-type separators are rare.

In this work, first results for the densification by uniaxial pressing of slurry-based separators with Li3PS4 electrolyte are shown. The separators were produced by dispersing the electrolyte and a binder in a solvent (xylene) and coating sheets via doctor-blading. Samples were punched with an area of 1.13 cm2 and 2.01 cm2. Subsequently, the impact of the densification temperature and pressure is investigated on the resulting density, porosity, adhesion strength and ionic conductivity. Moreover, the microstructure is analyzed by scanning electron microscopy. As one important result, an increase in embrittlement of the separator was observed with increasing densification pressure, which results in a deteriorated processability, and a higher risk for short circuit. Fortunately, higher temperature during compacting can provide mechanically more stable separators and results in a higher adhesion strength. Based on the obtained results, a performance estimation was carried out for batteries with the separators studied.

Evaluation of stabilisation techniques for Ni-rich cathode surfaces in ambient air.

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Lithium-ion batteries (LIBs) are the most developed energy storage systems for portable electronic devices and electric vehicles (EV) applications.[1] However, cathode materials with insufficient capacity are one of the factors restricting their utilisation. Therefore, the development of LIBs also emphasises the fabrication of novel cathode materials. Among them, Ni-rich layered oxide cathodes, such as NMC811, are one of the most feasible and attractive cathode materials for LIBs due to their high capacity and moderate manufacturing costs.[2-3] The primary problem of Ni-rich cathode materials in manufacturing is the reactivity of their surface in air, which affects the processability of the slurries into electrodes and can influence excessive capacity loss and limited cycle life in a battery cell. In addition, greater surface reactivity accelerates the onset of unfavourable responses. The formation of these surface Residual Lithium Compounds (RLC) on Ni-rich cathode material surfaces causes a rise in alkalinity, which can lead to gelatinization of the electrode slurry by defluorination of the binder, causing limited shelf life and dispersion issues during mixing. Moreover, water as the side product of RLC formation is able to decompose electrolyte salts, which can lead to dissolution of transition metals (TMs). These issues often mean that cathode coatings are conducted in dry atmospheres wherever possible. [4-10]

Here, we discuss Ni-rich NMC ($LiNi_{0.8}Co_{0.1}Mn_{0.1}O_2$) cathode materials stability in ambient air with Electro-Rite® Additive provided by Lubrizol Ltd. The polyether-based additive suppresses the formation of Residual Lithium Compounds on material surface. The evolution of RLC on the powder surface are monitored in real time using Fourier-transform infrared spectroscopy (FTIR) during exposure to air. Moreover, resulting coatings are shown to have limited impact upon material bulk structure and electrochemical performance, e.g. ions diffusion coefficient and long cycle life of battery. The observed findings indicate that additive-modulated surface coating provides a novel method for stabilising Ni-rich cathode materials in air by creation of physical protective barrier.

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Polymer extrusion process for solvent free, scalable production of all solid-state polymer electrolytes

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All-solid-state battery (ASSB) is the next generation battery technology, where classical liquid electrolytes are replaced with ion-conducting solids improving the safety of such a battery. The functionality of solid electrolytes (SEs) as separator preventing electron transport while conducting lithium ions enables the use of electrodes made of metallic lithium for high energy density ASSBs.

Polymer electrolytes are one promising material group, which are non-volatile and less flammable. The use of a thermoplastic polymer as matrix for SE gives a perspective to easily scale up its processing from laboratory scale to industrial series production. This enables the replacement of laboratory scale solvent based production methods, like doctor blading, through solvent-free extrusion, thus eliminating costly drying steps, which is ecologically and economically advantageous. Furthermore, the material properties and electrochemical performance of SE are not affected by any solvent residues. Hence, a twin-screw extruder offers the possibility of continuously mixing of polymer and conductive salt to produce homogeneous polymer based SEs. Additionally, using two feeding units eliminates a premixing step to obtain a homogeneous mixture of the components. Based on the capability of thermoplastic poly (ethylene oxide) (PEO) to dissolve alkali salts like LiTFSI, it is one of the most investigated materials for polymer based SEs.

The thermal processing route of PEO and its effect on the polymer properties is currently investigated. Previous works from our research group show that the processability of PEO not only depends on the conductive salt, but also on its molecular weight [1]. PEO is very sensitive toward thermal and mechanical load. The higher the molecular weight, the higher the sensitivity of the material that leads to degradation and chain scissoring even at small load.

The aim of this work is to optimize the extrusion process using a twin-screw extruder for the production of polymer based SEs. We investigate the effects of several extruder set-ups on the mixing behavior of $(PEO)_n$LiTFSI-electrolytes. Therefore, type of dosing, filling position and screw geometry are varied. Optimized process temperature and screw speed are used to avoid degradation of low molecular PEO. The decisive factor for this work is whether the desired composition is achieved after extrusion. For assessment of successful extrusion, we analyze the homogeneity and quality of the extruded product.

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Production of fiber-reinforced electrodes and separators for structural battery composites

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The European union set the goal to drastically reduce the environmental impact of the air transport sector with the Flightpath 2050 initiative. The development of full electric and hybrid electric propulsion technologies is crucial to achieve amongst others a significant reduction of greenhouse gas emissions until 2050. Due to the high energy consumption of aircraft the electrical energy storage is one main challenge. The specific energy of state-of-the-art batteries is not sufficient for the commercial air transport sector. One approach to address this issue is to reduce parasitic mass and volume by the multifunctional use of energy storage components. So-called structural battery composites can store electrical energy while bearing mechanical loads.

In this study, the storage of electrical energy is enabled in fiber reinforced composites commonly used for load-bearing parts in aircraft design by substituting the epoxy resin with the materials of an all-solid-state battery. The focus lies on the production and characterization of carbon fiber-based structural electrodes and structural separators based on glass fibers. A slurry composed of lithium iron phosphate (LFP), polyethylene oxide (PEO), Lithium bis(trifluoromethanesulfonyl)imide (LiTFSI) and carbon black was coated on carbon fiber textiles in order to prepare structural cathodes. With capacities of more than 125 mAh/g_AM good utilisation of the active materials in the structural cathodes is demonstrated. Structural separators prepared by either slurry coating or melt infiltration of glass fiber textiles with a PEO- and LiTFSI-based electrolyte were investigated and compared accordingly. The lamination procedure for structural electrodes and separators was found to have a significant influence on the electrochemical performance. Finally, the fabrication process of a structural battery composite demonstrator is presented. With respect to electrode and separator mass a power density of 64 Wh/kg was achieved.

Advanced Battery Materials: Processing of Lithium Metal Anodes for All Solid State Applications

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Through a largely establishing of electric vehicles in the market, an increase of energy density is needed. All solid state batteries are promises to be the next generation battery systems. While on the cathode side versatile materials and mixture recipes were examined, the anode side commonly consist of lithium metal. The processing of this material is an ambitious challenge caused by both the strong adhesion behavior and the highly reactive character of the alkali metal. Therefore, conventional process steps may not be suitable for the processing of lithium metal. To establish this material in commercial use, however, new framework conditions must be defined with regard to the processing steps.

In this work, the adaptions to the new material in terms of cutting and contacting are presented. For cutting, a thermal cutting, as well as an ultrasonic-based cutting method was applied. To compare and quantify the cutting success of the different cutting processes, the cutting edge, particle contamination and the influence of the ambient atmosphere were investigated and afterwards the cut electrodes were electrochemically characterized. In the contacting process, copper as a current collector flag was welded by ultrasonic on lithium foils. The resulting lithium-copper joints were investigated in terms of mechanical so as electrical properties.

Within this study, lithium-copper composite foil with 20 µm lithium on 10 µm copper substrate was cut. For thermal cutting, a pulsed ND.YAG laser with a wavelength of 1064 nm was used. Ultrasonic-based cutting was performed at an oscillation frequency of 35 kHz. Optical methods (digital light microscopy, laser scanning microscopy, scanning electron microscopy) so as the evaluation of the cyclo voltammetry were used to investigate the cutting success. For the contacting process, 10 µm thick copper foils were ultrasonic welded on a 10 µm pure lithium foil. Here, an ultrasonic welding machine with a frequency of 20 kHz was used. The mechanical properties of the joint were investigated by means of tensile shear as well as peel tests. Furthermore, the electrical properties were determined in terms of a 2-point conductivity measurement.

OPTIMIZATION OF HARD CARBON ANODES IN SODIUM ION BATTERIES

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Sodium-ion batteries (SIB) have been heavily researched, as a potential replacement for Lithium ion batteries (LIB) as their components are more readily obtainable, lower cost and they have similar working principles to LIB. Hard Carbon (HC) is as of now, the state-of-the-art anode for SIB material due to its relatively low cost, overall performance and availability. Enormous effort has been focused into improving and better understanding the overall mechanism of HC. One huge challenge remains, the volumetric expansion during the charging and discharging which is not completely understood and causes issues.

Here, recent attempts to design structured electrodes by incorporating different kinds of conductive additives and binders to combat the volumetric changes during cell charging and discharging are described. Results with different formulations and production techniques of Sodium-ion half cells are presented. High internal resistance was the major problem so far. The optimization of the formulation and cell procedure for hard carbon anodes, successfully resulted in the reduction of the internal resistance.

Roll-to-roll Prelithiation of Anode Materials - Status & Progress

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With rising performance requirements for lithium-ion battery technology, optimization of existing chemistries constitutes a key challenge for the coming years. Prelithiation proposes improvements in cell performance by increasing lithium content in existing cell chemistries. Lithium is added to either cathode or anode to minimize the initial capacity loss during formation and increase lithium availability over lifetime.

We present an overview of the working principle of prelithiation, expected performance impacts and different prelithiation methods. Research highlights different chemical, physical or electrochemical deposition methods, utilizing a number of lithium sources and deposition systems.

The poster focusses specifically on the electrochemical deposition system currently operated at our laboratory. This roll-to-roll system operates continuously, immersing the coated anode in different electrochemical and chemical baths. This approach allows to prelithiate the anode and pre-form a partial SEI in parallel. As a lithium source the process uses an electrolyte, composed of a lithium salt, solved in an organic solvent. Furthermore, the roll-to-roll system includes integrated washing and drying stations, to ensure optimal reproducibility and quality of the output.

The overall goal of operating a roll-to-roll prelithiation is further scale-up. To this end the entire system, especially electrochemical and machine parameters, is researched in detail. Our contribution gives insights in ongoing research activities. It highlights the current maturity of the process (Technology Readiness Level) and proposes next steps in research to enable industrial production.

Influence of process parameters on cathode properties of SPAN-based Lithium-sulfur batteries

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Sulfur with its high theoretical capacity of 1672 mAh/g is a promising Next-Gen cathode active material, but it still shows some major challenges. In comparison to other sulfur active materials, sulfurized polyacrylonitrile (SPAN) suppresses the parasitic polysulfide shuttle reaction through a one-phase solid-solid reaction leading to a high cycling stability of SPAN electrodes in comparison to other sulfur materials. Furthermore, the covalent bonding of sulfur to the PAN-backbone allows for the application of classical carbonate based electrolytes.

This study regarding the influence of different process parameters on the properties of SPAN-electrodes is based on established scalable production equipment like dissolvers and continuous coating and drying devices. The active material used was a SPAN produced by Adeka Corp. with 38 wt. % sulfur content and 90 wt.-% SPAN in the cathode. During the study the energy input as well as the amount of conductive agent (CA) and its composition were investigated. The results show a very important correlation between the production parameters, the structure of the CA-binder-network and the electrode properties regarding the necessary amount and type of CA to form a percolating network within the electrode. We demonstrated that carbon black with its small particle size and high networking-ability is the best option within the group of 3D conductive agents to reach good electrode properties with an electrical electrode conductivity at least 10 times higher than electrodes with other 3D conductive agents.

The results show the potential of SPAN for delivering high capacities over many cycles as well as high C-rates up to 1C with a water based and classical production process using already established production steps as well as common materials. This makes SPAN an easy to adopt material for next generation battery concepts, potentially processible in production sides already built for lithium ion batteries.

Recycling, circular economy and sustainability

Process Optimization of Li-Ion Battery Recycling

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Annual battery production is predicted to increase from 160 gigawatt-hours (GWh) today to 6600 GWh in 2030 for the mobility sector solely1. Such unprecedented battery demand requires resilience of the battery supply chain in which the recycling of distinct and critical materials (e. g. Lithium, Cobalt, Nickel,…), structural investment and planning are key. In this contribution, the flowsheet process simulation, implemented in the software HSC Chemistry, taking into account individual processes (i. e. pyrolysis, separation, hydrometallurgical processing, etc.) for the recycling of all key battery materials will be shown. The Li-Ion battery consisting of a graphite anode and NMC cathode has been chosen as a case study due to its commercialization scale. This approach in the first step supports the assessment of the economic feasibility and environmental impact of such batteries. In the second step, the model can be used to optimize the recycling process and identify important factors influencing material quality for reuse. This work is embedded in the SIMTEGRAL project, which is a part of the Excellence Cluster Recycling & Green Battery (greenBatt). The herein presented approach can potentially be expanded and applied to other cell chemistry, such as Na-ion batteries.

Fine grinding of pyrometallurgically produced battery slags for dissolving and recovery of lithium

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Lithium-ion batteries have been applied in a large number of industrial and private applications in the last few years, which automatically increased the production rate of these electrochemical storage devices. Their large quantities of valuable materials, such as nickel, cobalt, and copper, lead to an enormous ecological footprint and make battery-recycling indispensable. As one recycling strategy, pyrometallurgical recycling has become established because it is extremely robust to varying material flows and impurities and offers improved scale-up potential compared to hydrometallurgical processes. However, a major disadvantage of pyrometallurgical recycling is insufficient recovery of lithium, which is typically lost as a component of slag. To recover lithium from the slag, leaching was established on lab scale. Current challenges regarding the scale-up of the leaching process deal with high energy consumption, large quantities of leaching agents, and comparably low lithium concentrations in the slag [1, 2].

These challenges were addressed by a comminution process to actively reduce additional thermal energy and the amount of leaching agent. The enormous increase in the specific surface area and change of crystalline structures based on mechanical stresses improved the solubility of lithium-containing phases in an aqueous environment. Through a variation of the operating parameters, the effect of the comminution process on the dissolution process was understood. It was found that increased stress energies and longer process times lead to an improved dissolution of lithium and therefore enable a process optimisation with regard to lithium recovery and energy input.

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Direct Recycling of Electrode Scrap

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Economic and sustainable battery cell production is an indispensable requirement for electric vehicles to become an important part of the energy revolution. That is why the development of efficient recycling processes and novel recycling strategies is part of numerous research projects. The aim is to close the material cycle in battery cell production to the greatest possible extent, thereby reducing costs and significantly improving the CO2 footprint. In this context, the production scrap also has to be taken into account, most of which is already generated during electrode production. Since the electrode scrap is purely of the electrode type (anode or cathode), direct reprocessing offers a significant advantage. Therefore, the aim of our research is to directly recycle the electrode scrap by means of mechanical processes and not to recycle them in the conventional way together with battery cells, which would contaminate the material. This enables the direct production of electrodes with the black mass obtained without further costly processing steps such as hydrometallurgical treatment.
In this study, the recycling of electrode scrap is carried out via a comminution process (e.g. cutting mill) followed by a screening process (e.g. air jet sieve). Furthermore, in some cases a pre- or post-treatment (e.g. thermal) of the electrodes is carried out before or after the comminution in order to facilitate the separation of the coating mass from the current collector. The process parameters were systematically varied and the influence on the separation of the coating mass as well as on the contamination of the resulting black mass (BM) was investigated. In addition, other important product and process properties such as particle size, morphology, yield, etc. are considered. In summary, this study shows that cathode and anode black mass can be recovered from electrode scrap with low impurities and, thus, can be used directly for electrode production.

Potentials of design modifications to improve the recyclability of lithium ion batteries for mobile applications - An investigation to quantify recycling-oriented design guidelines by means of statistical entropy

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The European Union (EU) is pushing for the establishment of a circular economy in the area of consumer and traction batteries. The aim is to keep them in the use phase as long as possible. In order to update the Directive 2006-66-EC (on batteries and waste batteries), new standards and regulations will establish soon in the EU. For the first time, great importance allocated to product design. It can be determined, that the design and composition of products have a significant influence on recycling or closed loop materials flow.
Complex products, such as lithium-ion battery systems for electric vehicles, are currently optimised in terms of performance, energy density and costs. Aspects of a recycling-friendly design of cells, modules and systems have so far only been given secondary consideration. For this reason, entire systems are sent for material recovery at the end of the first life cycle, since removing individual components from the battery system is only possible with a great deal of technical and organisational effort. With regard to optimised recyclability of current and future batteries, modules and systems, the sortability, dismantlability of components and separability of materials as well as the technological incompatibility of materials and design solutions are also important criteria. It is necessary to take a closer look at the effects of product design on the recyclability of products.
From the perspective of battery development, the following question emerges in the context of recycling-friendly designs: "How can different design solutions be compared with each other in terms of their recyclability?" This paper deals with the quantification of recyclable design adaptations with the help of statistical entropy. This study therefore focuses on the quantification of recycling-friendly design modifications with the help of the evaluation of statistical entropy. Based on Bognar et al. (1) & Roithner et al. (2), we developed an evaluation methodology that calculates recyclability based on product information such as material composition and product structure. The goal is to create an evaluation basis that makes it possible to design products more recyclable and sustainable in the early development phases and to make product designs comparable with each other. The methodology is validated based on an analysis of existing e-bike accumulators and identifies impediments as well as potentials for improvement.

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Data Acquisition and Management in Mechanical Lithium-Ion-Battery-Recycling - An Enabler for Data-Driven Research

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Batteries are highly integrated products composed of mixed materials that are highly affected by energy-intensive processing, security of supply, and raw material criticality. Therefore, a battery circular economy is needed which requires efficient recycling processes on the material level to enable sustainable raw material recovery. The recycling of lithium-ion batteries is a distributed system of individual procedures like mechanical treatment, thermal treatment, hydrometallurgy and pyrometallurgy that are combined into several conceivable process routes. To this point there exists no data-driven approach to map and optimize the battery recycling process chain.
In this work, we focus on the data acquisition in the mechanical treatment within the battery recycling process chain. Requirements for successful data-based approaches in battery recycling are presented. Moreover, we show our data acquisition and data management strategy to support data-driven approaches in LIB recycling. Several potential use cases for primary data from battery recycling are suggested to uncover potential interrelations within the recycling chain and to provide data for further applications (LCE, safety, maintenance, monitoring, etc.).

Environmental Assessment of Sulfidic All-Solid-State Battery Pouch Cell Production

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All-Solid-State batteries (ASSB) are a promising technology for reaching targets for capacity, fast-charging capability and safety of batteries. However, methods for a holistic evaluation of potential production routes and their transferability to industrial scale are still subjects to research. The investigation of different production concepts mainly focuses on the processing based on sulfide, oxide, polymer and hybrid-based solid electrolytes. In our current research we aim to analyze distinctive process chains for the named solid electrolyte classes in order to evaluate their scalability as well as their techno-economic and environmental impact. The sulfide-based process chain is promising based on the high ionic conductivity and processing properties of the electrolyte for a scalable production. However, the release of H2S during production makes this route challenging, so safety parameters for sulfidic solid electrolytes are also being investigated.

The focus of this work is to assess the environmental impacts and identify key hotspots of a potential sulfide-based production route for ASSB pouch cells. Therefore, a cradle-to-gate Life Cycle Assessment has been conducted. Expert opinions on the processes, laboratory-scale energy measurements, as well as background data from the ecoinvent database have been incorporated into the python-based modeling using Brightway2. The results show that especially the electricity demand and the consumption of argon represent a high environmental impact. The high argon demand is driven by the use of an inert environment required in the processing of the highly reactive sulfides and metallic lithium. Hence, optimizations in terms of energy and process efficiency are among the main challenges. Based on this, recommendations are developed by considering potential micro environments and scale effects to pave the way for high-energy and sustainable battery production.

Graphite Recycling from End-of-Life Lithium-ion Batteries Through Heating Processes

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Very fast-growing markets of lithium-ion batteries (LIBs) for hybrid, plug-in, and electric vehicles, and many portable electronic devices that are produced and discarded every year may pose risks to supply lines of limited resources (such as Cobalt, Nickel, Lithium, Aluminum, Copper, or Graphite materials). Thus, recycling and regeneration of end-of-life LIBs (EoL-LIBs) is becoming an urgent and critical task for a sustainable and environmentally friendly future. In this regard, much attention, especially in industry, has been expended on developing recycling of cathode materials, such as transition metal oxides, but not much attention has been dedicated to the recycling and reuse of graphite from EoL-LIBs. As the most commonly used anode material, graphite is vital to the battery industry, and it is classified as a supply risk material, therefore, recovery and reusing of graphite is an important task in the battery recycling industrial lines. The spent graphite was under many aging mechanisms, such as Li intercalation/de-intercalation into graphite, solid electrolyte interphase (SEI) formation, which could result in structural changes and particle degradation. Furthermore, the recovered graphite could have some metal/metal oxide impurities while performing the recovery processes, consequently, all of these issues would affect the electrochemical performance of this material. Hence, further purifications should be carried out for reusing recovered graphite as a LIB anode, and it should be with high purity and as free as possible from impurities. Herein, after an acid leaching, the obtained graphite from the black mass (mixed anode and cathode electrodes) is subjected to heating treatment from 500 to 1500 °C, and the best condition is optimized for the spent graphite from EoL-LIBs. Additionally, the graphite samples are tested as the anode of LIBs and electrochemical evaluation is investigated in detail.

The Influence of Cationic and Organic Impurities on the Heterogeneous Lithium Carbonate Precipitation

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In commercialized hydrometallurgical lithium-ion battery (LIB) recycling processes, metals from the cathode (e.g. cobalt, nickel, manganese, lithium) are recovered through acid leaching from comminuted electrode material (black mass) and a subsequent precipitation sequence. During this process, the desired metals are selectively precipitated through a step-wise increase of the solution pH value. However, lithium is generally recovered at the end of the precipitation sequence from a solution containing ionic impurities from the previous leaching and precipitation steps.

In the presented work, lithium carbonate precipitation is examined within a LIB recycling process recovering lithium previously to the leaching step of the black mass. In the examined process, water is added during comminution of the LIB cells, so that water-soluble lithium salts and organic electrolyte constituents of the comminuted battery cell are dissolved in an aqueous phase. However, most of the other elements from the metal oxide cathode remain in the solid fraction from where they can be leached subsequently. This work focusses on the recovery of lithium carbonate through heterogeneous precipitation from the aqueous solution during a carbon dioxide scrubbing process in a 350 mL stirred reactor. The precipitation process is monitored using pH, temperature and particle size tracking probes to generate a detailed understanding of the process. In particular, the influence of remaining cationic and organic impurities on the lithium carbonate product yield and purity is investigated.

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Biopolymer gel electrolytes for zinc-based batteries

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The current development towards electric mobility requires continuous improvement of battery technologies. Lithium-ion batteries (LIBs) set todays benchmark regarding battery performance and cycle life. However, the increased distribution of portable electronics and the demand for smart grid energy storing technologies forces the need for safer, more sustainable and greener battery materials at low costs. Zinc-based batteries are considered suitable candidates as one of the “beyond lithium-ion” technologies due to their safer aqueous alkaline electrolyte, lower cost and specific power and energy close to LIBs [1]. Gel polymer electrolytes (GPEs) offer a great opportunity to avoid common challenges of zinc-based batteries such as zinc anode derived dendrite growth or shape-change during cycling. Moreover, GPEs pave the way for flexible and leak-proof batteries. Not only on behalf of their sustainability but also because of their structural diversity, the present investigations are targeted on the development of suitable biopolymer-based GPEs for zinc-based batteries.

The biopolymer xanthan showed its suitability as a GPE at various concentrations in a nickel zinc battery (NiZnB). The NiZnB with a 200 g/L xanthan electrolyte resulted in a successful cycling for 200 cycles with similar initial discharge capacities of 250 mAh/g compared to the reference NiZnB with a glass fiber separator and a liquid alkaline electrolyte. However, the NiZnB with bio-based GPEs needs improvement in terms of poor capacity retention and lower coulomb efficiencies compared to the control reference. Besides xanthan, other biopolymers such as bacterial cellulose and alginate are also being investigated as GPEs due to their functional groups, mechanical properties and availability. These biopolymers are combined and varied in their concentration in the electrolyte formulation to be compared in terms of mechanical stability and electrochemical behavior. These results are an important step towards a more sustainable battery development and are beneficial for future zinc-air batteries, which face similar challenges as the NiZnB regarding anode aging.

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Direct lithium-ion battery recycling using dielectrophoretic separation

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With the increasing demand for batteries, especially due to the steadily growing market of electromobility, considerate handling of resources is essential. Therefore, effective strategies and processes have to be implemented in the battery fabrication routines in order to overcome intercontinental material dependences and to derive economic benefits. Respectively, recycling of used batteries and the containing compounds and materials becomes immensely important, also in respect to achieving a circular economy with high recycling ratios for strategically valuable elements. Nevertheless, pyrometallurgical and hydrometallurgical state of the art methods are cost-intensive and economically unattractive, while their recovery efficiencies are unsuitable for large-scale application at the same time. One solution to substitute these methods and to tackle the necessary recycling issue is the use of dielectrophoretic separation. This easily implemented, scalable and eco-friendly technique is based on the induced motion of particles in an electrical field. Due to the difference in their physical properties, particles within the black mass can be selectively separated, whereas no additional chemicals are needed. In our contribution we want to give a detailed insight into the recycling process via dielectrophoresis and show first results of material separation and respective efficiencies.

Wet-Mechanical Processing of EoL-LIB to optimize the Recovery of Lithium and other Materials

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Current research and development in the recycling of end of life lithium-ion batteries (EoL-LIB) mostly focusses on the recovery of metals such as cobalt or nickel. This research project is taking the three major challenges in current recycling processes into account: 1) optimizing the recovery of lithium 2) optimizing the separation of the black mass from the electrode foils 3) optimizing the recycling of the coarse fraction. Leading lithium recovery processes currently lack high recovery rates due to the loss of the electrolyte within the process. The wet-shredding process shall optimize the recovery of Lithium with the discharge of the electrolyte into the fluid phase. The planned poster will bring special emphasis to the wet-shredding of LIB-modules - which reduces time consuming deloading and dissembling of EoL-LIB modules – plus the recycling of the coarse fraction > 2mm, which is treated via mechanical and sensor-based sorting steps to optimize the recovery rate for other materials such as copper, aluminum, iron and plastics. The planned poster will show first results such as the amount of composite materials in the shredder output, as well as in which fractions to find the desired materials – both varying depending on the screen outlet inside the shredder. Further lessons learned include additional needed processing of the shredder output to separate the black mass from the coarse fraction.

Determination of lithium aluminate content in lithium-ion battery slag using short-wave ultraviolet and picture analysis

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With the increasing use of lithium-ion batteries and higher demands on raw materials for battery production, recycling has gained a significant meaning. A frequently used process in the recycling of lithium-ion batteries is pyrometallurgy. The considerable advantage of this route is its robustness to the input material. However, due to the material properties and characteristics of lithium-containing structures and crystals, recovering this element from the slag is a big challenge. Another issue regarding lithium recycling is quantifying and qualifying the amount of lithium present in different fractions during the liberation from the slag. The usual chemical and analytical methods are not simply applicable to determine lithium content. For instance, it is impossible to use elemental analysis such as SEM-EDX for lithium. Therefore, analytical techniques such as ICP-OES and SEM-MLA are used. Although these methods show valuable and reliable results especially in research, they are time-consuming and costly. They are not practical for quality control and in-line analytics during recycling processes on a large scale.
This research focuses on developing a quick and novel method to determine lithium content in different fractions during comminution and separation. The slag material used in this study contains lithium aluminate crystals. These crystals are thermodynamically designed and grown during the pyrometallurgical processes to reach a grain size of 50-200 µm. These crystals can absorb short-wave ultraviolet and radiate red light. A picture analysis tool is used to detect certain color hues matching the color of radiations from pure lithium aluminate and measure their intensity. Combining this intrinsic property with the picture analysis tool makes it possible to find a quick and cheap analysis method to recognize and quantify the amount of lithium aluminate in the samples. To evaluate this method, XRD and ICP-OES are applied additionally.

Challenges and potential approaches for the disassembly of end-of-life traction battery systems in preparation for further mechanical processing

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With the strong market diffusion of battery electric vehicles over the last couple of years, the number of returning batteries will also increase significantly in the near future. This development poses new challenges for subsequent processes and in particular for battery disassembly as an introductory step before remanufacturing or recycling. The DemoSens project analyzes the process of battery pack disassembly regarding the large variety of products and different topologies and identifies resulting challenges. The core of the solution concept is the build up of a robot system in a pilot plant which aims to automate the disassembly down to the module level at the example of one battery type. The implementation of robotics is intended to create a process for disassembly that can be used dynamically but is in the same time robust. As part of the solution concept, the design of the end effectors in connection with various graspingand process scenarios will be addressed.
To enable the robot to autonomously perform the corresponding work steps the automated localization and pose estimation of components using camera systems and computer vision algorithms are researched. Here, instance segmentation and pose matching algorithms are utilized. Another aspect is the self-learning of robot trajectories for rather undefined disassembly tasks. By combining these and other partial solutions into a plant concept, the project attempts to gain important insights into the design and improvement of the battery disassembly process. First results and conclusions regarding the guidance of the robot will be addressed.

Green batteries for clean skies: Sustainability assessment of all-solid-state lithium-sulfur batteries for electric aircraft

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Battery-electric aircraft are currently being developed as part of the efforts to decarbonize the air transport sector. Due to technical restrictions regarding the maximum take-off and landing weight, high specific energy of the battery is crucial. A promising technology in this context is the lithium-sulfur all-solid-state battery (LiS-ASSB). It enables high specific energy of up to 472 Wh/kg at pack level, which corresponds to an increase of 70% to 80% compared to state-of-the-art lithium-ion battery technologies. However, suitable solid electrolytes and related battery system designs are still in the research and development phase.
While the usage of such batteries in electric aircraft reduces the environmental impacts of flight operation, the materials required for battery cells, as well as the energy-intensive production processes, are associated with new environmental and socio-economic challenges, potentially leading to burden shifting. Therefore, this presentation provides first insights concerning the sustainability of LiS-ASSB for electric aircraft. Based on electrochemical models, solid electrolytes for LiS-ASSB are selected, and the battery systems are designed. Subsequently, a sustainability assessment is conducted to analyze the environmental and socio-economic impacts of battery production. They are compared to a lithium-sulfur battery with a liquid electrolyte as a benchmark.
The analysis indicates that sulfides are the most suitable inorganic solid electrolytes for electric aircraft batteries. In addition, the cradle-to-gate investigation reveals that the new LiS-ASSB technologies are advantageous in terms of low environmental and socio-economic impacts. However, the battery configuration with the best technical characteristics is not necessarily the most promising in terms of sustainability. Especially variations from the technically optimal cathode thickness can further improve the reduction of environmental and socio-economic impacts.

Pyrometallurgical process modelling of slags from lithium-ion batteries based on coupling CALPHAD with finite element analysis

Haojie Li
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Due to its high energy density combined with lightweight construction, the demand of Li-ion batteries (LIBs) in the field of portable devices, hybrid- and battery-driven vehicles is continuously increasing. However, with the enormous growth of LIBs manufacturing arises the challenge of recycling the lithium from LIBs after reaching their end of life. The combined pyrometallurgical and hydrometallurgical process route shows a promising potential to enrich and regain the lithium in the form of the high lithium bearing phase $LiAlO_2$ from the slag. Leading components of LIB slags are Li-Al-Si-Ca-Mn-O. To improve the recycling efficiency of this route, one challenge thereby is to understand and even predict the complex interrelationship between the initial composition, processing temperature and the amount of the target product LiAlO2, which is formed during solidification. Generally, CALPHAD is a very promising approach for modelling the composition and solidification route influence on phase formation. However, this approach delivers the information in one material point, such that the influence of spatial fields is not considered. On the process level, this is a critical issue, because, e.g., spatial temperature fields are present. In this work, a model is developed where CALPHAD is directly coupled with the finite element method, such that spatial temperature fields for various apparatus-specific topologies can be taken into account. Based on an updated database for the Li-Al-Si-Ca-Mn-O system, slag solidification of this system is simulated by directly coupling CALPHAD with the finite element method. The influence of different temperature fields on the LiAlO2 formation during solidification for certain compositions is investigated. Hence the influence of process boundary conditions and apparatus topology on the LiAlO2 formation is simulated and studied. It can be shown that this approach is highly valuable in pyrometallurgical engineering.

Model based assessment of closed-loop battery recycling systems

Steffen Blömeke

TU Braunschweig | Institute of Machine Tools and Production Technology (IWF)

The need for sustainable mobility requires measures to reduce the impacts along the product life cycle. One mitigation option is the closed-loop use of products, components and materials, with resulting increased interactions and interdependencies between production and recycling. Recycling should not be evaluated independently but as part of the overall system of closed material loops. This enables the joint evaluation of material quantity and quality and their intended use in new Lithium-ion batteries. Computational modeling approaches are needed to represent the complexity of these system dependencies and provide decision support for recycling planners. This contribution will evaluate different recycling systems on process chain and unit process level. Based on a hotspot analysis, optimization approaches for specific recycling processes will be presented.

Thermodynamic modelling of the thermally induced release of electrolyte solvent mixtures in the lithium-ion battery recycling process chain

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Due to the increasing demand for lithium-ion batteries (LIB) in many areas of application, such as electromobility, stationary energy storage and electronic devices, the need for resources is increasing continuously. In the context of limited resources and sustainability, the recycling of LIBs is of particular importance. Meanwhile, several technologies for LIB recycling have been developed, which are at different readiness levels. One particular process step, which is of high relevance in the recycling process chain of LIBs is the controlled release of electrolyte solvents. Example solvents are EMC, DMC, EC and DEC. A tailored fractionated release of these solvent mixtures is necessary in order to increase the recycling efficiency in downstream processes as well as the energy efficiency of the process itself. Consequently, sophisticated simulation approaches, which are able to predict the release of electrolyte solvents under certain processing conditions, e.g. temperature, and initial electrolyte solvent loads, are indispensable. In this work, the statistical rate theory (SRT) is coupled with CFD, which enables for the first time the prediction of the release of electrolyte solvents for different process parameters, where the respective solvent can be tracked individually and hence the fractionation process can be understood in detail on the microlevel considering molecular information. By coupling the SRT based model with CFD the scale transition is provided, such that the separation macro processes can be simulated, while information on the molecular scale is taken into account directly.

Impact of adding solid electrolyte interphase constituents as impurities on cell performance of lithium-ion batteries

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The growing numbers of electric vehicles will lead to a significant amount of returned lithium-ion batteries (LIB). Due to the potential of LIB as source of secondary raw materials and their environmental risks if improperly disposed of, their recycling is of increasing interest for the development of a sustainable and closed loop system. During recycling, the electrode materials and electrolyte, among others, can be purified partially. Yet, some impurities remain, e.g., metals from the current collector. Other impurities originate from the solid electrolyte interphase (SEI) of spent LIBs. These impurities, both organic and inorganic compounds, may contaminate the LIB made from recycled material. To date, little is known about the impact of these impurities on the performance and lifetime of LIB.

For research purposes, SEI constituents are added separately to the electrolyte as known impurities during LIB production. This way, their individual influence on the SEI formation and aging can be investigated. Experiments are performed with three-electrode cell setups. For identifying the impact of impurities, electrochemical characterization methods such as capacity tests, electrochemical impedance spectroscopy or C-rate tests are used as well as post-mortem analysis of contaminated LIB. Based on the obtained findings, the influence of impurities, known to be SEI constituents, on the performance and lifetime of LIB can be discussed.

Life Cycle Assessment of novel anodes based on Silicon

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Technological advances are expected to promote environmentally sustainable development. New materials and components development for battery technologies should then be accompanied by environmental impact studies. In this sense, Life Cycle Assessment is a powerful tool in order to determine and overcome the environmental impacts [1].

New electrodes for lithium ion batteries based in a promising material for anodes such as silicon are developed so as to overcome current graphite restrictions related to safety issues and limited theoretical specific capacity. Silicon is considered an anode material for next generation lithium ion batteries due to its outstanding properties but it also presents serious barriers related to its stability and cycle life. Modification of silicon anodes with carbon materials has demonstrated to overcome these issues [2].

In this work Life Cycle Assessment of developed anodes based in silicon/graphite blend and silicon/carbon composite is carried out. First of all, modification of current graphite anode with silicon is performed. However, graphite is considered a critical raw material and its manufacturing is characterized by energy intense production process [3]. Graphite could then be subtituted by other carbonaceous materials with no supply issues. Carbon materials coming from abundant carbon rich wastes could be a promising type of materials for their co- utilization with silicon in Lithium battery anodes.

Comparative Life Cycle Assessment of both anodes shows lower impact of silicon/carbon anode in terms of carbon footprint. The life-cycle inventory for material and energy consumption inputs to electrodes production includes from raw materials acquisition, wet dispersing, coating and drying, through to the calendering, fixing the anode structure and final slitting.

The aforementioned tool also allows to determine the origin of total impact so as to take actions to reduce it. In case of developed anodes total impact is mainly assigned to requiered energy, raw materials transportation and copper foil used as current collector. Further measures could be implemented to reduce the carbon footprint obtained.

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Mechanical Processing of LIB Components with the Use of Sensor-Based Material Detection in the Context of High-Quality Recycling

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End-of-life lithium-ion batteries (LIB) from electric vehicles are usually disassembled manually in the first step of recycling. Fractions such as cables, screws, pack housings and busbars are recovered in the process, which is known as the periphery. This consists of different materials or material composites depending on the battery pack. Subsequently, the LIB modules are shredded under an inert atmosphere, wet or after thermal treatment, and processed using conventional processing steps such as screening, sifting etc. In addition to the black mass, further fractions such as shredded electrode foils, which are made of aluminum and copper as well as shredded module housings made of aluminum, stainless steel and / or plastic have to be recovered. In the current research project, the different components of the battery pack will be identified in order to separate the different materials and metal types already in the dismantling process. A handheld X-ray fluorescence is used for this purpose, as it is a fast, flexible and non-destructive method. In further project steps, the module housings are automatically processed in greater depth after crushing and preparation with the aid of a stationary sensor system. The aim is to use sensor-based sorting to generate output streams from disassembly and mechanical processing that can be sent for higher-quality recycling. For this purpose, the output is analyzed and evaluated before and after the use of sensor-based sorting. In the poster planned here, material composition measured with handheld X-ray fluorescence will be shown. Furthermore, first (sensor-based) sorting results will be presented and evaluated in the context of high-quality recycling.

Towards a better recycling of Li-ion batteries by recovery of electrolyte solvents from shredded cells

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A high degree of sustainability of lithium-ion batteries (LIB) is achieved by establishing a circular economy, thus in improving the battery recycling process leading to an increase in resource efficiency. In comparison to state-of-the-art recycling processes mostly based on pyrometallurgy, processes combining mechanical and hydrometallurgical treatment - as investigated in the LOWVOLMON project - promise to significantly enhance the overall recovery rate by further increasing the yield of precious high-value materials such as Lithium (Li) compounds and by additionally recovering lower-value materials like graphite. [1] However, in the mechanical shredding of the LIBs, the liquid organic electrolyte solvents are released.
The shredded material needs to be dried to low residual solvents in order to achieve high separation efficiencies in the hydrometallurgical steps. [2] From an economic point of view, the optimization of the drying time and conditions is of major interest. The description of the drying process is particularly complex due to the presence of a multi-component mixture with different thermodynamic and material transport properties as well as due to the influence of the porous structure of the shredded material. Drying and sorption experiments will be conducted to provide data about the mass transfer kinetics and phase equilibria. Various measurement techniques will be employed to capture component-specific drying curves and to quantify the organic electrolyte components before and during drying. [3, 4]
Finally, a simulative model of the drying process is to be developed. This is to calculate the critical process times and to optimize the process depending on the boundary conditions, thus reducing costs. Moreover, with the knowledge of residual loadings the safety of the overall recycling process is enhanced. In the end, the findings gained about drying step in the LIB recycling can be used for the improvement of existing and the development of innovative industrial scale plants.
This work contributes to the research performed at CELEST (Center for Electrochemical Energy Storage | Ulm & Karlsruhe) and Material Research Center for Energy Systems (MZE). The authors would like to acknowledge financial support of the Federal ministry of Education and Research (BMBF) via the greenBatt cluster-project "LOWVOLMON" (Grant number: 03XP0354C).

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Inductive heating as a thermal recycling pretreatment for Li-ion electrodes

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In view of the growing demand for stationary and mobile energy storage applications, the recycling of Li-ion cells is an important opportunity to make resource use more sustainable, reduce greenhouse gas emissions and lower cell costs.
In addition to Li-ion cells that have reached their end of life, rejects are already generated during the cell manufacturing process. These rejects also contain valuable materials and need to be recycled. Due to a multitude of cause-effect relationships within the manufacturing process that are not fully understood, the reject rates in Li-ion cell production of approx. 5 to 10 % are significantly higher than in other areas of industrial production.
Production rejects from Li-ion cell production differ from end-of-life cells because these have not yet undergone any material ageing and can be regarded as effectively pristine. In addition, the material composition is known . These circumstances require the development of processes specially designed for the recycling of production rejects. Valuable scrap battery materials should be treated in-house and reintroduced directly into the process chain. In this way, long transport routes and extensive recycling routes can be avoided and the material cycle can be closed within production.
With this background, an inductive heating of coated current collector foils is being investigated as a thermal pre-treatment for the recycling of lithium-ion cathodes. For this purpose, production rejects are heated in a continuous process in order to heat the polymer binder above melting point or decomposition temperature and thereby weaken the adhesion of the coating and the current collector foil. The cathode materials and the foil are then separated in a cutting and impact mill.
The main objective of the investigations was to assess the feasibility of the process. To evaluate the process, the separation efficiency of the coating material and film as well as the degree of contamination of the recyclate were determined. From this, the recycling rate for the cathode material was calculated and correlated with the temperatures approached.
In addition, the recyclate was examined by XRD with view to its crystal structure and by XPS for possible passivation of the active material as a result of binder decomposition.

Conceptual design of a condition-based disassembly of lithium-ion batteries - from cell to electrode level

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In the recycling of lithium-ion batteries, disassembly as the first recycling step decisively defines the recycling strategy. To date, mainly battery systems and modules have been disassembled on the basis of an upstream condition assessment. The disassembled components are then fed into a mechanical shredding process and subsequently chemically recycled. Due to the variety of battery systems, modules, and all other components to be shredded, complex sorting and filtering processes are required to separate the economically and ecologically valuable active materials in a high degree of purity. Especially the separation of the anode and cathode active material from the passive materials (e.g. housing structures) is intricate.

Extending the depth of disassembly to the disassembly of cells and electrodes can provide early and potentially low-effort separation of active materials with high purity. This extension requires novel concepts for disassembling cells down to the electrode level. Based on a survey of the requirements for cell disassembly processes, the presented research shows various concepts for extending the disassembly depth in an economically and ecologically feasible way. The concepts are discussed regarding the achievable variant flexibility of the battery cells to be disassembled, the condition-based choice of the disassembly depth as well as the possible automation. As a result, the concepts contribute to the extension of disassembly in the recycling of lithium-ion batteries.

Developing robust and scalable recycling routes for cathode active materials in lithium-ion batteries

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Sustainable material concepts are particularly important for advancing the mobility transformation. Especially the cathode active material contains valuable metals that are only available in limited quantities in the world, therefore it is essential to regain these raw materials. Currently, this recovery is still carried out on a very small scale and the recycling route is subject to certain fluctuations due to the varying raw material qualities. Bearing this aspect in mind, the focus of this work is to evaluate and establish robust and scalable process strategies to produce cathode active materials from secondary raw materials.

Nickel-rich layered oxides have attracted great interest as active materials at the cathode side due to their high useful capacity. In this work, their synthesis was carried out by co-precipitation because this process is also often used for the synthesis from primary raw materials and is easily scalable. The goal of this work is to investigate what impurities occur in the resynthesized material, how they affect the material properties and how the impurities can be reduced during processing. For this, a deeper understanding of the process-structure-product relationships is essential.

The synthesis was initially tested on primary raw materials and various reaction systems (round bottom flask, reactor, mill) were established. In the process, the chosen parameters were adjusted to generate optimum properties of the materials. This process route is then applied to the secondary materials. Special attention must then be paid to the impurities contained, as these can influence the product properties. For this purpose, process-companying analytical methods must be applied to monitor the properties.

System integration and application

Lithium-Plating diagnostic and their integration in a battery management system

Mauriz Kahmann

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Lithium plating is a major limiting factor of the fast charging process, while a maximum possible current is required to speed up the charging process in terms of user friendliness. One approach to achieve the highest possible current during charging is the adaptive current control through a detection methodology that detects lithium plating in combination with a plating minimising fast charging strategy. An in operando detection methodology was tested, which detects plating by means of low sensor effort with a current and voltage measurement. Target applications in a conventional BMS are feasible. The in operando methodology was compared with an in situ methodology based on the observation of voltage relaxation profiles. The in situ methodology has a sensitivity of a few per cent of irreversibly deposited lithium. The in operando methodology can be more sensitive with a correspondingly accurate measurement technique. The limiting factor is the parameter changes of an ageing battery, which makes a generalisation of the methodology difficult.

Hybrid modelling of Lithium-ion batteries: Proof of concept for application of Physics-informed Neural Network in Electrochemical battery modelling

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The capability to accurately forecast lithium-ion battery (LiB) lifetime and its degradation is a major bottleneck in LiB system optimization and management. The complex cell design parameters coupled with wide variation in usage conditions makes the LiB lifetime evaluation challenging and slow. In the past, physics-based (PB) models have shown significant success in describing cell behaviour and early-stage capacity fade. However, physical description of the dynamics of cell behaviour using large number of parameters, makes a PB model complex and one needs to achieve a compromise between physical accuracy and complexity. Simultaneously, the emergence of machine learning (ML) models has generated rapid prediction methods based on descriptors learned purely from data. ML models operate by recognizing patterns in data, and are not affected by the underlying physical processes. However, the ML models require large training datasets and are also prone to failures when generalizing to scenarios unseen in training. ML models are unlikely to bring high-accuracy health forecasting transferable to situations beyond the available data, without any consideration of physical processes.

This indicates the need for a novel approach that hybridizes the two models and can tap into both their advantages. The goal of this study is to integrate the PB battery model and ML model to leverage their respective strengths in order to calculate the state of health of LiB cells. This is achieved through the extension of physics-informed neural networks (PINN) to an electrochemical battery model. This approach directly implements a single-particle electrochemical model based on Fick's law of diffusion within a deep neural network framework. PINNs take into account the underlying differential equations, i.e., the physics of the problem, rather than attempting to deduce the solution based solely on data, i.e., by fitting a neural network to a set of state-value pairs. PINN exploits the recent developments in automatic differentiation to differentiate neural networks with respect to their input coordinates and model parameters to obtain a physics-informed neural network. Hence this approach of integrating PINN with differential equation of a single particle model will provide an insight on how the integration of the PB and ML models can improve one's ability to forecast the battery state of health.

The hybrid model introduced in this study will be integrated with the digital twin a of battery cell and battery module. A central requirement of battery digital twins is to reflect the actual ageing and degradation of the physical battery. Using PINN for battery digital twin implementation to predict the state of health helps to meet this requirement by learning the physical dynamics of a battery in terms of differential equations and automatically updating the model parameters based on their solutions. This is a novel approach to implement the model component of a battery digital twin that can learn the physics of battery ageing and reflect the same in the lifetime predictions made by the model.

Selection of a separator as an important factor for the safety of a battery cell

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Nowadays lithium ion batteries (LIB) became one of the key technologies for energy storage in different kind of applications because of their high energy density and their advanced stage of development. Therefore, LIB's are not simply rated by their performance parameters but also by issues of safety. With respect to the interaction of electrical and chemical hazards as well as emergence of fire and explosions, the thermal runaway represents the main risk potential related to the extended use of LIB's. For safety studies a thermal runaway can be provoked by different events which can be analyzed via temperature and voltage monitoring, as well as measurements of gaseous products and post mortem studies.

A possibility to analyze the behavior of a LIB in case of deformation resulting from abusive behavior is the crush test. With increasing deformation, the mechanical stress in the contact area of the cell also increases. If a critical stress is exceeded, damage to the separator occurs, which allows electrical contact between the electrodes and can result in a thermal runaway. Different separators have different mechanical and thermal properties, so the start and progress of these reactions can vary greatly. Therefore, this study presents the results of crush tests with cells using different separators in a custom-made battery cell investigation chamber. This chamber allows the determination of parameters which influence the response of battery cells to internal short circuits. The response is analyzed via measurement of cell voltage, temperatures, as well as camera recording, and FTIR spectroscopy to identify and quantify infrared active gas species. The similarities and differences of the effects of the separator choice on the electrical, thermal and chemical response are explained and the changes in the mechanical behavior discussed. Furthermore, it is shown to what extent separator pre-tests are able to directly predict the outcome of the crush test.

ProZell
Kompetenzcluster
zur Batteriezellproduktion

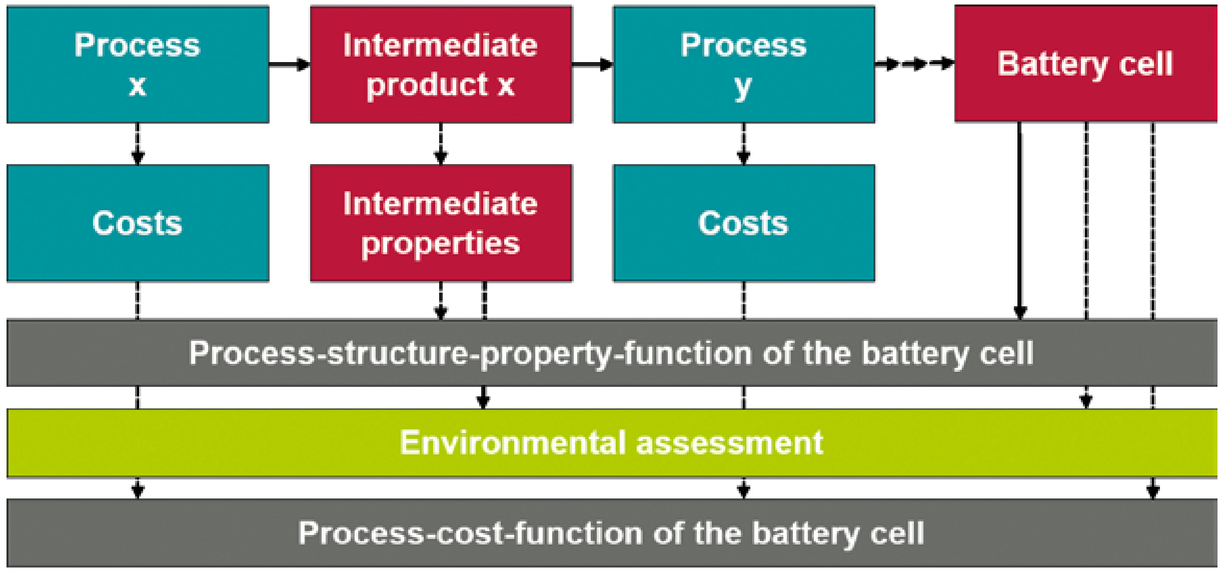
ProZell – Competence cluster for battery cell production – Influences of production steps and parameters on cell performance and quality – Challenges and goals

In the competence cluster for battery cell production (ProZell), German research institutions join forces to strengthen the national battery cell production. The aim of the competence cluster is to research and improve the entire process chain of the battery cell production and assess the influence of each individual production step on cell properties, product development costs and sustainability. The competence cluster elaborates the scientific basis for the establishment and sustainable development of an internationally leading, competitive battery cell production in Germany. In this context, the economic efficiency of cell production and the environmental assessment are highly relevant. While aiming at reducing the energy-related cell price (€/kWh), the competence cluster pursues the simultaneous goals of increasing cell performance, especially energy density, and elaborating recycling pathways for battery cells.

The central concept of the cluster is to cross-link specific knowledge, special equipment, and various research institutions in joint projects. In 16 research projects, experts and scientists from various fields of expertise collaborate on identifying variables that cause relevant changes in intermediate product properties, as well as cell performance, quality, and costs. Process-structure-property relationships and process-cost-functions along the entire process chain of the battery cell production are developed. An accompanying project fosters cooperation and networking within the entire cluster and ensures a structured bundling of knowledge in a results database. In addition, an advisory board including representatives from industry and research advises the projects and fosters synergies between research institutions and industry.

Contents and main areas of work

The continuous production of battery suspensions by extrusion, in addition to increasing the energy density through the targeted structuring of high-capacity electrodes and the use of silicon are areas of focus for the field of electrode production. A pre-lithiation technique adds lithium to the anode prior to cell assembly in order to increase the stability of lithium ion battery cells containing silicon during charging and discharging cycles. A novel dry-coating technology allowing for solvent-free electrode production diminishes the need for energy cost during expensive drying procedures and opens the door towards environmentally friendly electrodes. In addition, interactions between process control and product properties are investigated in detail, especially for calendering and post-drying of electrodes. Within the field of cell production, the optimization of filling and wetting processes, taking into account all essential cell components, is topic of intensive research. The energetic optimization of cell formation is investigated. The investigations regarding cell stack formation focus, above all, on the special requirements of high-energy electrodes. Overarching projects in the cluster focus on developing innovative quality assurance concepts to reduce fluctuations and rejection rates and to optimize the interlinked production processes with regard to an appropriate definition of production tolerances. Based on mathematical models for the entire process chain, the detailed understanding of related process-structure-property relationships is used in order to digitally describe the entire process chain and optimize it for new battery generations. Further points of interest are the comprehensive cost and environmental assessment of the process chain and the recycling of battery cells. A results database brings together key findings of the projects in a transparent manner.



Application, use of results and contribution to energy storage

The properties of electric vehicles and systems for the electrochemical storage of energy as well as their respective customer benefits correlate directly with the properties of the battery cells used. A better understanding of influencing variables along the entire process chain, including the production environment, is therefore essential. The establishment of an economical and sustainable battery cell production is the central milestone on the way to establishing Germany as a leading market and provider of electro-mobility. The fundamental challenge for competitive battery cell production is to increase cell performance while simultaneously reducing the energy-related cell price (in € per kWh). The knowledge gained in the competence cluster should form the essential basis for the development of economically producible battery cells, i.e. battery cells with a significantly improved performance-to-cost ratio. The results provide a scientific basis for achieving and continuously

expanding the sustainable, international technology and cost leadership of all German industries involved in the value chain of cell production.

Partners and funding

Currently, the ProZell competence cluster comprises 19 partners, including the following universities and research institutions: TU Braunschweig, Karlsruhe Institute of Technology, Landshut University of Applied Sciences, TU Berlin, TU Clausthal, TU Dresden, TU Bergakademie Freiberg, Center for Solar Energy and Hydrogen Research Baden- Württemberg, German Aerospace Center via the Helmholtz Institute Ulm, Ulm University, RWTH Aachen University, TU Munich, Münster Electrochemical Energy Technology (MEET) at University of Münster, Fraunhofer-Gesellschaft, Forschungszentrum Jülich via the Helmholtz Institute Münster, University of Bayreuth, August-Wilhelm-Scheer Institute, Leibniz Institute for New Materials, and Aalen University.

The ProZell cluster was funded by the Federal Ministry of Education and Science (BMBF) with more than 16 million euros in the first funding period from 2016 to 2019. Due to the promising results and the good cooperation and collaboration within the ProZell competence cluster, the BMBF has been intensifying its financial support for battery research since 2019. The second funding period of ProZell started on October 1st, 2019 and comprises more than 35 million euros in total funding. The successful ProZell concept serves as a model for the establishment of further competence clusters by the BMBF, namely: InZePro – Intelligent battery cell production, greenBatt – Recycling/Green battery, BattNutzung – Battery use concepts, AQua – Analytic/Quality assurance.

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