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PRODUCTION OF AN ALL-SOLID-STATE BATTERY CELL

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Batterieproduktion

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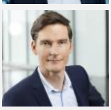

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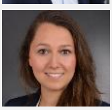

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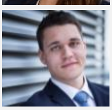

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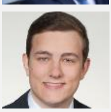

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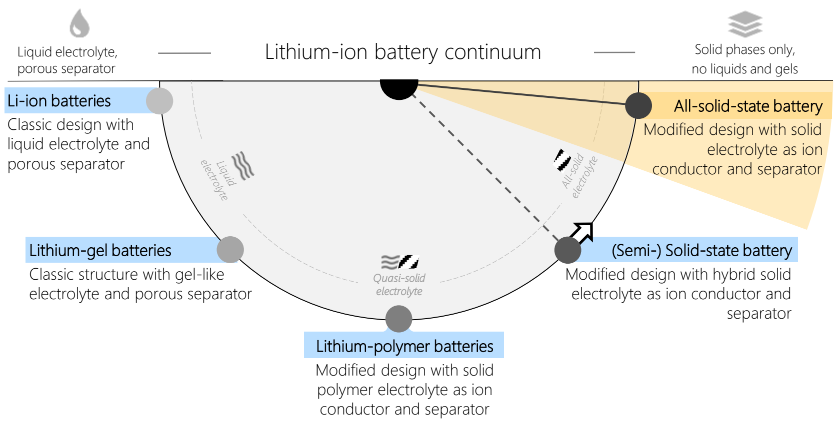
All-Solid-State battery

What does the future of the battery look like?

Higher energy and power densities, longer lifetimes, increased safety and significant cost reduction – this is the **ideal vision for future battery technologies**. With its profile, the **all-solid-state battery** promises **to set new standards** in several of these dimensions.

But despite **considerable progress**, the all-solid-state battery still faces several **challenges** on its way to becoming an industrialized energy storage device that can be used in various products. These can be divided into the **product- and process-related activity fields** and are specifically addressed within the framework of current research and development activities.

Starting with the classic lithium-ion battery, the **development path towards the solid-state battery** is characterized by a **continuous change in the internal cell structure** and the **production technologies** used for its manufacturing.



Potentials

- **High energy densities** using pure lithium anodes
- **Minimized explosion and fire risk** due to elimination of liquid electrolyte
- **Shortened charging times** due to high power density
- **Wide operating window** in the temperature range from -30°C to +100°C

Challenges

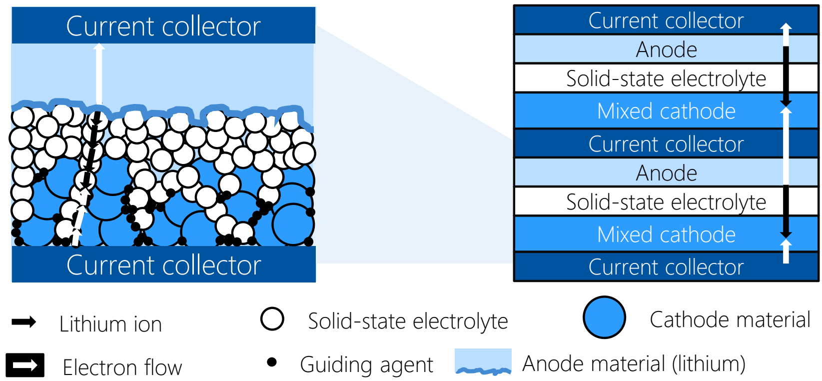
- **High interfacial resistance** between the solid phases
- **Lack of compatibility** between solid electrolyte and electrode materials
- **Lack of manufacturing processes** for series production
- **Reduced production costs** for competitiveness

This brochure focuses on the production of the all-solid-state battery and provides initial answers to questions about changes in the manufacturing process.

Structure & Functional Principle

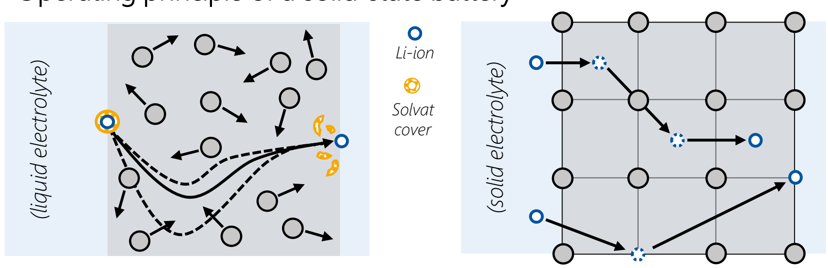
of an all-solid-state battery

Structure of a solid-state battery



- In principle, various cell designs are possible for solid-state batteries. The illustration above schematically shows the **basic structure of a solid-state battery** with a **mixed cathode** and a pure **lithium metal anode**.
- Within the all-solid-state battery, a **solid-state electrolyte** permeable to ions acts as a spatial and electrical separator between the cathode and the anode. This also serves as the function of an insulating separator between the two electrodes.
- The use of a solid electrolyte also offers the possibility of **bipolar stacking**, which is defined by a **serial connection of individual monocells**.
- Depending on the number of stacked monocells, **significantly higher voltages** are already possible at the cell level.

Operating principle of a solid-state battery



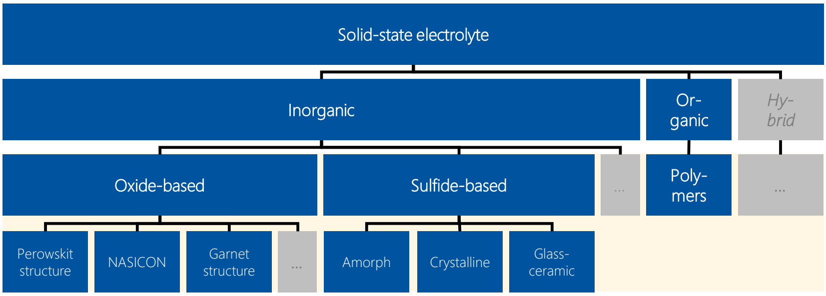
- During the **discharge process** of an all-solid-state battery, the lithium ions move from the anode through the solid electrolyte to the cathode. At the same time, a current flows through the closed external circuit.
- **Free spaces within a predefined grid structure** enabling the lithium-ion transport inside the solid-state battery.

Materials

of an all-solid-state battery

Solid-state electrolyte

- Solid-state electrolytes can be divided into **organic and inorganic electrolytes**. Inorganic electrolytes typically include **oxide** and **sulfide-based electrolytes**. They offer advantages in safety as they are neither flammable nor do they contain toxic materials.
- **Organic electrolytes** include **polymers** and **polymer/ceramic composites**. The latter tries to combine the advantages of inorganic and organic electrolytes in a targeted manner.



Sulfide-based

- Sulfide-based electrolytes can be divided into **crystalline**, **amorphous** and **glass-ceramic phases**.
- They have **high ionic conductivity** and deformability, which is why they offer several advantages for solid-state batteries.
- The main disadvantage of sulfide-based solid-state electrolytes is the **limited stability** towards the **lithium anode** and the **cathode materials** as well as a pronounced **reactivity** in the **standard atmosphere** (formation of toxic H_2S).

Oxide-based

- Oxide-based electrolytes have an **extended electrochemical stability window** and are less reactive than sulfide-based electrolytes.
- The high **hardness and deformation stability** of the oxide-based electrolytes help to prevent the formation and growth of dendrites.
- However, the **ionic conductivity** is often significantly **lower** than that of **sulfide-based electrolytes**.

Polymer-based

- Polymer-based solid electrolytes consist of a **conductive polymer matrix** containing a lithium salt which is conductive for lithium ions.
- Compared to the other electrolyte classes, these have **high deformability**, which proves to be particularly favorable for the formation of the interfacial contacts to the electrodes.
- The main disadvantages are the **low lithium-ion conductivity at room temperature**, the lack of **temperature stability** and the **limited electrochemical stability window.**

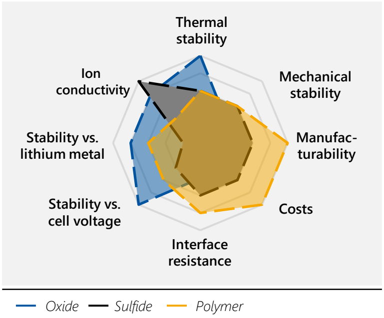
Materials

of an all-solid-state battery

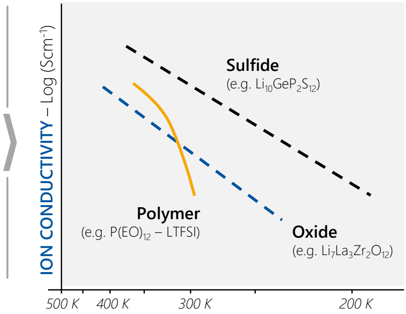
Comparison of solid-state electrolytes

- The direct comparison of the solid electrolyte classes illustrates the different property profiles and shows the development areas to be prioritized in further optimization.

PROPERTY PROFILE – Solid-state electrolytes



TEMPERATURE – (Kelvin, K)



Anode materials for the solid-state battery

- **Graphite** and **lithium titanate** are typical anode materials that can also be used in solid-state batteries.
- The focus in realizing solid-state batteries is on using **pure lithium metal anodes** (the focus of the process description) which promise the **highest energy densities** due to their high specific capacity.
- If used as anode material, lithium metal tends to **form dendrites**, which can only be partially prevented by using a solid-state electrolyte. In addition, handling in an inert atmosphere is necessary, as otherwise, a **passivating surface layer** forms immediately.
- An alternative is **silicon**, which also enables **increased energy densities** but faces the challenge of massive **volume changes** during operation.

Cathode materials for the solid-state battery

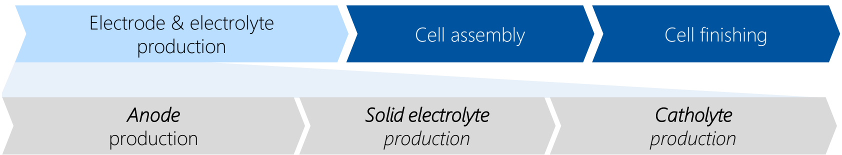
- Metal oxides such as **nickel-manganese-cobalt compounds (NMC)** or **lithium-iron-phosphate (LFP)** are typical cathode materials that can also be used in solid-state batteries.
- In a deviation from the conventional cathode formulation, the **active material is mixed with the solid electrolyte** for the solid-state battery. Often referred to as **"catholyte"**, this new compound is necessary to ensure **sufficient ionic conductivity** inside the electrode.

Production Process

of an all-solid-state battery

Main sections in the production of solid-state batteries

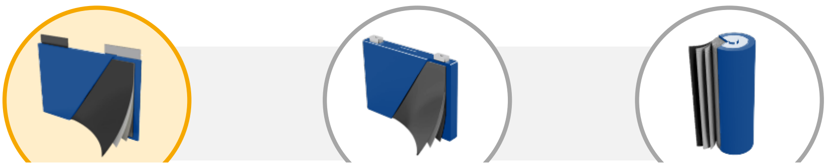
- The production of an all-solid-state battery can be divided into three main stages: **electrode and electrolyte production**, **cell assembly** and **cell finishing**.
- The main section of electrode and electrolyte production comprises **anode**, **cathode** or **mixed-cathode** and **electrolyte production**.



Process chains in the manufacture of solid-state batteries

- A generally applicable and established process chain to produce solid-state batteries does not yet exist. Instead, many **different production processes** can be used. The **required production volumes** and methods depend primarily on the processed solid-state electrolyte.
- In this brochure, a **complete and coherent process chain** is considered for the **three electrolyte classes** (oxide-based, sulfide-based and polymer-based). These are oriented towards **scaled production on a pilot line or series scale** and are based on a **pouch cell** in the cell format.

Cell formats to produce solid-state batteries



Pouch cell — Prism. cell — Cylind. cell

Stacking is advantageous to produce solid-state batteries, as the electrode and solid electrolyte layers are not additionally deformed and exposed to critical stresses in this case. The cell stack can then be compressed over its surface and inserted into the housing.

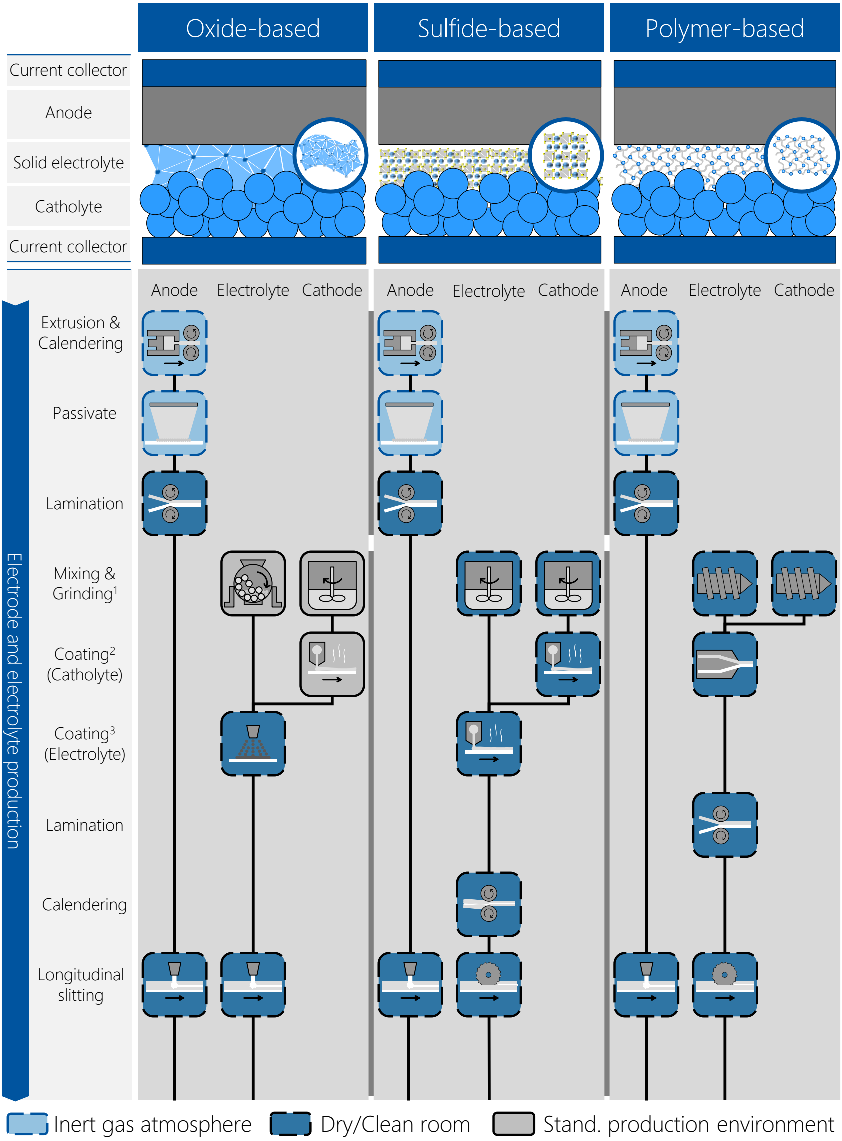
Windings or "jelly rolls" are hardly possible due to the solid components of the solid-state battery and are associated with significant challenges. For some electrolyte classes, such as brittle oxide ceramics, these cannot be realized without defects.

The following process chains and technology profiles provide an overview of the scaled production of all-solid-state batteries.

Production Process

Electrolyte-specific process overview

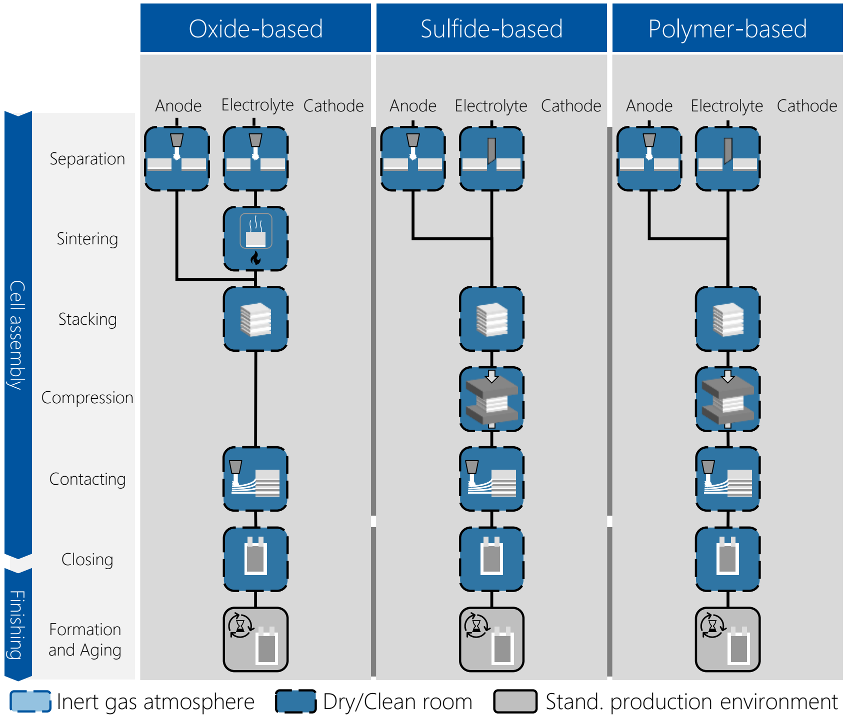
- In **electrode production**, the **composite of cathode**, **electrolyte** and **anode** is produced.
- The central **differentiating feature** of the various solid-state batteries is the **production** of the **solid-state electrolyte**:



[1] From left to right: Ball mill, planetary mixer and extruder
[2] From left to right: 2x Tape casting, co-extrusion
[3] From left to right: Aerosol deposition and tape casting

Production Process

Electrolyte-specific process overview



Electrode production

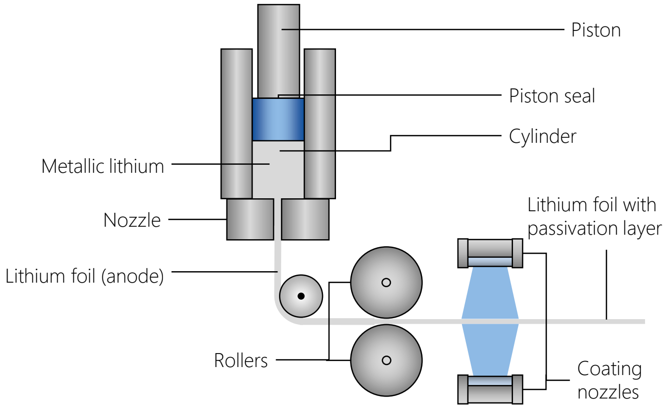
- The **product** of the anode production for these technology chains is a **lithium foil**, which later forms the **negative electrode** in the cell compound and is required in a similar form for all three technology chains.
- The **product** of the cathode production is the **positive electrode** of the elementary cell. The production varies depending on the electrolyte material and the cell structure used later. In the process chains shown, the **cathode is used as a substrate for the electrolyte layer production**. This composite of cathode and solid electrolyte is then combined with the anode.

Cell assembly and cell finishing

- The **cell assembly and finishing processes** are similar for the technology chains presented. In the first step of cell assembly, the half cells and the **anode sheets are separated** and **stacked** to obtain the desired cell structure. Depending on the electrolyte material, the cell stack is **compressed** after the stacking process.
- In the next step, the **cell stack is contacted**. The cell stack is placed in an electrically insulated package which in the case of pouch cells consists of a metal-plastic mixture. The **battery cell** is **already charged** during the stacking process due to the lithium metal anode.

Piston Extrusion

Anode production



Cell assembly | Cell finishing

Process description

- The forming is done via an extrusion process in which lithium – present as lithium metal ingots – is pressed through a slot-shaped exit cross-section and thereby formed into a foil.
- Homogeneity, surface roughness and final film thickness are ensured after extrusion by subsequent calendering. For this purpose, the film is rolled through two rollers under pressure and temperature control.
- Optionally, after the production of the lithium foil, the lithium is coated with a passivation coating. The surface passivation enables further processing of the lithium foil in the dry room instead of an inert gas environment.

Further information

- The rollers must be compatible with the adhesive surface of metallic lithium. Among others, plastic rollers can be used for this, e.g. ones made of polyacetal.

Process parameters & requirements

- Extrusion speed
- Temperature of the lithium (up to 100 °C)
- Pressing force of the piston (1.000 – 10.000 kN)
- Lubricant feed speed
- Roller speed
- Nozzle geometry

Quality features

- Foil thickness
- Film width
- Homogeneity of the lithium foil
- Surface roughness
- Passivation layer

Challenges

- Adhesion tendency and reactivity of metallic lithium

Technology alternatives

- PVD process[1]
- Lithium coating from the molten phase

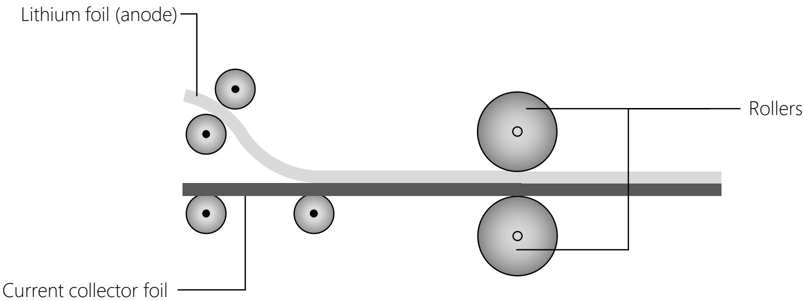
Transferability of competencies from the production of lithium-ion battery cells[2]

low **1** 2 3 4 5 high

[1] Physical vapor deposition
[2] New process step compared to the lithium-ion battery (LIB)

Lamination

Anode production



Process description

- After production and subsequent surface passivation of the lithium foil it is laminated onto a current collector foil. For this purpose, the lithium foil and the current collector foil are brought together via rollers.
- In the next step, the two layers are pressed together by two rollers. Tempering the rollers increases the adhesive forces of the composite produced.

Further information

- The laminated sheets can be obtained directly with different thicknesses of the two foils (lithium and current collector foil).

Process parameters & requirements

- Feeding speed of the layers
- Temperature control/temperature
- Roller speed
- Calendar gap
- Line pressure (< 2.500 N/mm)

Quality features

- Adhesion between the layers
- Foil alignment
- Uniform layer thickness

Challenges

- Adhesion tendency of metallic lithium during lamination
- Mechanical cutting methods are unsuitable due to the lithium

Technology alternatives

- PVD process[1]
- Liquid coating (with lithium in molten state)

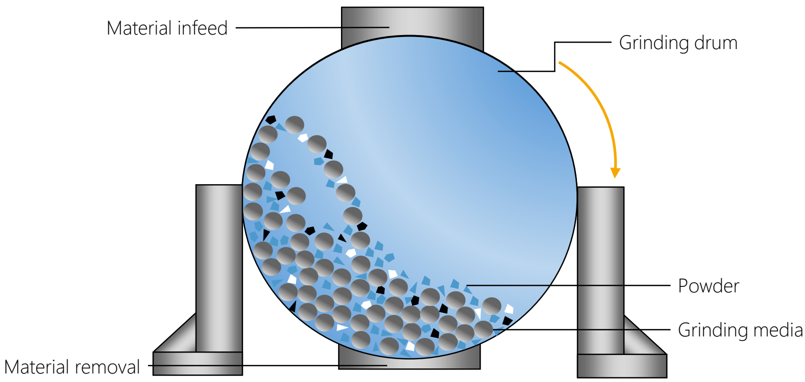
Transferability of competencies from the production of lithium-ion battery cells[2]

low 1 **2** 3 4 5 high

[1] Physical vapor deposition
[2] New process step compared to the LIB

Mixing & Grinding

Electrolyte material preparation



Process description

- The electrolyte powder can be produced in a ball mill. For this purpose, the starting materials are put into a cylindrical grinding drum where ceramic grinding balls are located, without adding any liquid. The drum is then set in rotation.
- The rotational movements of the cylinder result in the mixing of the starting materials. The rotational movement ensures a relative movement between the grinding media and the starting material, whereby the latter is ground until the electrolyte powder is reduced to a defined particle size.

Further information

- The powder is then calcined to obtain the desired powder properties (minimizing subsequent shrinkage of the oxide electrolyte powder).
- The cathode material can be produced similarly in a ball mill.

Process parameters & requirements

- Grinding time (1 – 10 h)
- Grinding speed (approx. 500 min^{-1})
- Atmosphere (installation site): Clean room or no requirement
- Quantity of raw materials
- Ball-mill material (e.g. ceramic)
- Ball-mill diameter (1 – 10 mm)

Quality features

- Average powder particle size
- Homogeneity of the powder (degree of mixing)

Challenges

- Abrasion of the grinding media

Technology alternatives

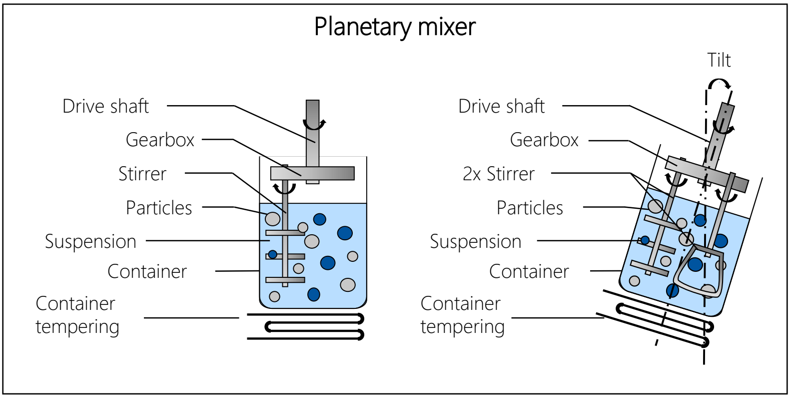
- Vibratory mill
- Planetary mill
- Attritor mill
- Agitator mill

Transferability of competencies from the production of lithium-ion battery cells[1]	low	1	2	3	**4**	5	high

[1] Similar process step with adapted production technology

Mixing

Electrolyte material preparation



Process description

- In planetary and intensive mixing, the materials are mixed in powder form with an agitator in a container.
- Optionally, the powder mixture of the active cathode material is dispersed by the addition of a solvent (e.g. NMP) and binders to form a slurry.
- Most sulfidic materials are sensitive to polar solvents and moisture, which limits the choice of compatible/usable solvents.

Further information

- Intensive mixing is also often referred to in the context of planetary mixers. Characteristics are additional features in the form of additional mixing tools (fast/slow rotating), vacuuming/tempering of the mixing container and the option to tilt the container by up to 30°.
- When mixing highly viscous slurries, a geometry free of dead space is essential so that the tools capture agglomerates faster and reduce process time.

Process parameters & requirements

- Mixing time (0,1 – 1 h)
- Agitator speed (100 – 10.000 min^{-1})
- Temperature control (30 – 50 °C)
- Atmosphere (in the mixer/installation site): Inert gas or vacuum/dry room etc.
- Tank filling level
- Inclination of mixing vessel (10 – 30°)

Quality features

- Homogeneity of the slurry
- Agglomerate size
- Free of bubbles
- Purity (foreign matter content)
- Viscosity

Challenges

- Avoidance of agglomerates, inhomogeneities, abrasion, sedimentation, concentration gradients and separation

Technology alternatives

- Acoustic mixing
- Ultrasonic mixing
- Centrifugal mixing

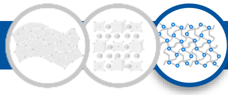
Transferability of competencies from the production of lithium-ion battery cells[1]

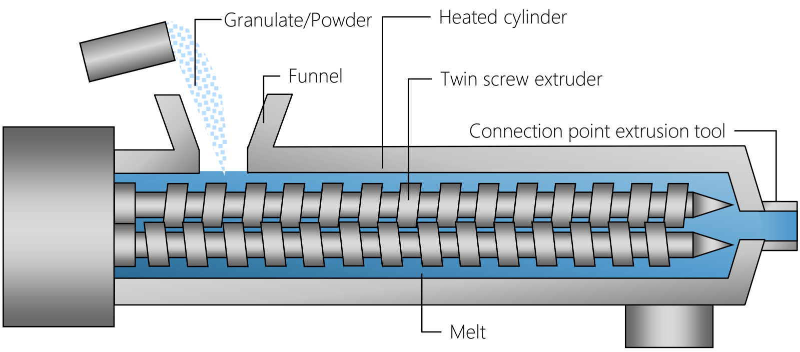
low	1	2	3	4	**5**	high

[1] Identical process step compared to the LIB

Compounding

Electrolyte material preparation





Process description

- The cathode and electrolyte melts are produced in two separate compounding processes.
- The material components are fed into the heated barrel of a twin-screw extruder and can be in the form of granules or powder.
- Through rotational movements of the extruder, energy is introduced into the material components. This creates a homogeneous melt.

Further information

- In addition to cathode active material, electrolyte particles, binders and additives are added to the cathode melt. The introduced electrolyte particles reduce the interfacial resistance between the cathode and electrolyte layers.
- The main components of the electrolyte melt are electrolyte particles and polymer binders.

Process parameters & requirements

- Mixing time (<1 h)
- Extruder speed and torque
- Cylinder temperature (20 – 100 °C)
- Atmosphere (in the mixer/installation site): Inert gas or vacuum/dry room etc.
- Dosage
- Shear energy

Quality features

- Homogeneity of the slurry
- Agglomerate size
- Free of bubbles
- Purity (foreign matter content)
- Viscosity

Challenges

- Avoiding inclusions, agglomerates, concentration gradients and pores

Technology alternatives

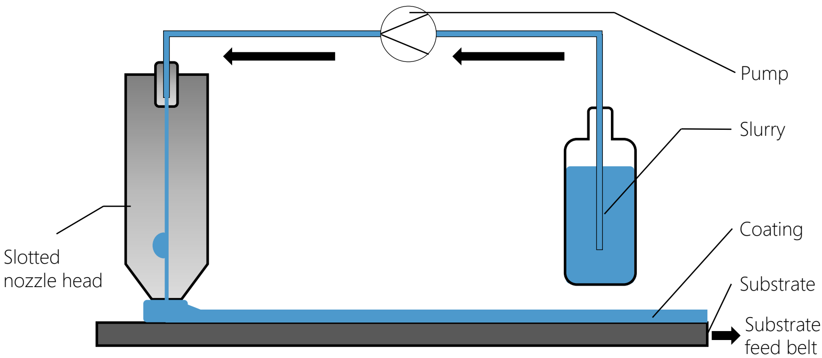
- Rotor-stator mixer

Transferability of competencies from the production of lithium-ion battery cells[1]	low	1	2	3	**4**	5	high

[1] Similar process step with adapted production technology

Tape Casting

Cathode and electrolyte production



Process description

- In slot nozzle coating, the slurry is conveyed through a feed hose using a pump and applied to the substrate using a slot die.
- With slot nozzle coating, the slurry can be applied on one or both sides and continuously or intermittently.

Further information

- Flawless coatings require reliable application tools and place demands on solvents, such as freedom from bubbles.
- In addition, the fluid must be supplied evenly and without pulsation.
- This is followed by a drying step in which the solvent is evaporated. Ideally, a solvent recovery option is provided.

Process parameters & requirements

- Band speed (25 – 100 m · min^{-1})
- Gap height slot nozzle head/substrate
- Temperature profile in the dryer zones: 50 – 160 °C
- Solvent recovery
- Foil pretension

Quality features

- Coating thickness accuracy (homogeneity in and across the coating direction)
- Surface quality (voids, particles)
- Adhesion between coating and substrate

Challenges

- Avoidance of layer thickness variations due to changes in production conditions

Technology alternatives

- Extrusion
- Roller coating
- Screen printing

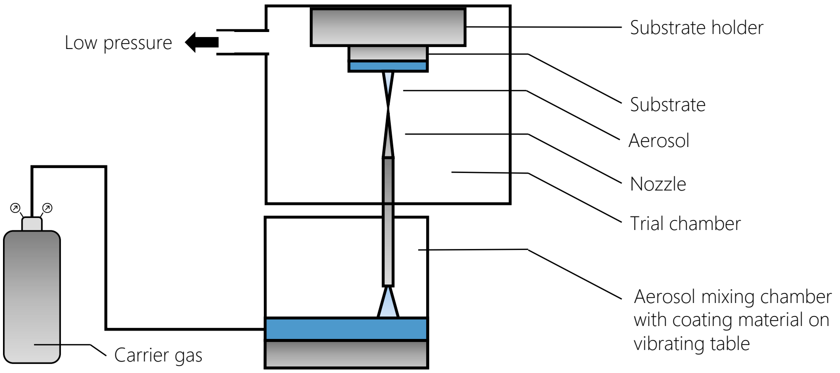
Transferability of competencies from the production of lithium-ion battery cells[1]

low 1 2 3 4 **5** high

[1] Identical process step compared to the LIB

Aerosol Deposition

Electrolyte production



Process description

- Aerosol deposition is a layer-generating process and belongs to the thermal spray processes.
- In aerosol deposition, the solid electrolyte powder is mixed with a carrier gas stream (e.g. air, N_2, O_2, Ar oder He) on a shaking table to form an aerosol.
- The aerosol is then accelerated at high speed towards the substrate (here, cathode or catholyte).
- On impact, the coating particles are deformed into a dense, firmly adhesive layer.

Further information

- Aerosol deposition takes place in a process chamber which can optionally be temperature-controlled or in which negative pressure can be generated. In addition, further protective gases can be used.

Process parameters & requirements

- Coating rate (< 10.000 µm · h^{-1})
- Mass flow powder (< 100 g · min^{-1})
- Jet velocity (100 – 1.000 m · s^{-1})
- Distance nozzle/substrate
- Mixing chamber temperature (< 200 °C)
- Pressure aerosol chamber (0,0001 – 1 bar)

Quality features

- Constant layer thickness
- Low surface roughness
- Homogeneity and purity of the coating
- Adhesion between coating and substrate

Challenges

- Low deposition rate
- Avoidance of excessive surface roughness
- Material sensitivity (damage to particles, unstable layer structures)

Technology alternatives

- Plasma syringes
- PVD process[1]
- CVD process[2]

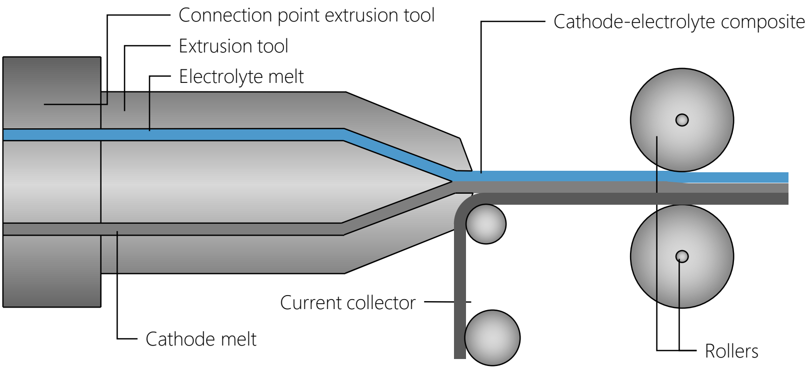
Transferability of competencies from the production of lithium-ion battery cells[3]

low **1** 2 3 4 5 high

[1] Physical vapor deposition
[2] Chemical vapor deposition
[3] New process step compared to the LIB

Co-extrusion

Cathode and electrolyte production



Process description

- The cathode and electrolyte melts are co-extruded in a suitable tool. The cathode and electrolyte melts are each fed through the extrusion tool under high pressure via a separate channel. In the process, the extrusion tool creates the cross-section of the extrudate, in this case, the composite of the cathode and electrolyte layer.
- In the next step, the layers are pressed together by two rollers during lamination. In the process, they are heated to achieve higher adhesive forces. During the heating and pressing, polymers penetrate from one layer into the other and thus form the connection of anode and electrolyte.

Further information

- The melts pass through the channels to the outlet of the extrusion tool. Here, the melts are extruded via a slot die onto a current collector or onto a carrier belt to produce thin layers, depending on the intended cell stacking.

Process parameters & requirements

- Band speed
- Feed rate of the melts
- Tempering/temperature
- Extrusion pressure
- Roller speed
- Line load

Quality features

- Adhesion between the layers
- Alignment of the layers
- Uniform layer thickness and width
- Desired bond thickness

Challenges

- Different process temperatures of the materials

Technology alternatives

- Tape casting
- Screen printing
- Roller coating

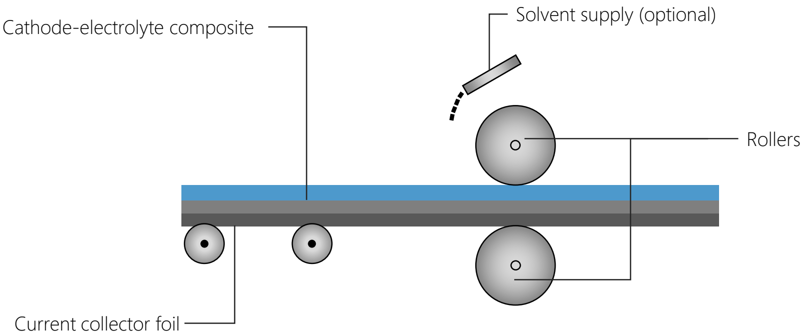
Transferability of competencies from the production of lithium-ion battery cells[1]

low	1	**2**	3	4	5	high

[1] New process step compared to the LIB

Calendering

Cathode and electrolyte production



Cell assembly | Cell finishing

Process description

- During calendering, the cathode-electrolyte compound is compressed by applying pressure and temperature. The pressure is applied by calendering rollers, whereby the electrode foil must not be damaged in the process.
- The layer thickness of the electrode foil can be adjusted by the width of the gap between the rollers.
- For ductile sulfidic and polymeric solid-state electrolytes, the calendering process is necessary to achieve improved performance properties of the composite by applying pressure and tempering.

Further information

- The oxide-based electrolytes are sintered, which is why the calendering process is not necessary.

Process parameters & requirements

- Feeding speed of the composite
- Tempering/temperature
- Roller speed
- Calender gap
- Line pressure (< 2.500 N/mm)
- Feed speed of the lubricant

Quality features

- Adhesion between the layers
- Alignment of the layers
- Uniform layer thickness and width
- Desired bond thickness

Challenges

- The high compressive stresses during calendering of brittle inorganic electrolyte layers with a relative density of up to 100 %

Technology alternatives

- none

Transferability of competencies from the production of lithium-ion battery cells[1]

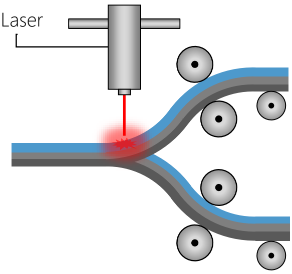
low 1 2 3 4 **5** high

[1] Identical process step compared to the LIB

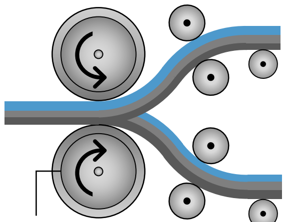
Longitudinal Slitting

Cathode and electrolyte production

Longitudinal separation by laser



Longitudinal separation by roller blade



Cell assembly | Cell finishing

Process description

- In the last step of the electrode and electrolyte production, the electrode foils are divided into several electrode strips with the required width by slitting.
- Length cutting is done mechanically with the aid of rolling knives or using laser cutting.

Further information

- The forces created using the rolling knife can lead to a deflection of the substrate, cracks and delamination of the coating. With laser cutting, such errors are avoided because the separation of the material takes place without contact.
- Contactless laser cutting requires less maintenance than cutting with roller knives.
- A danger in laser cutting is layer delamination due to the different melting temperatures of the materials in the layer composite.

Process parameters & requirements

- Cutting speed
- Spot size
- Pulse energy and duration
- Pulse repetition rate
- Laser power or line energy
- Wavelength

Quality features

- Clean cut edge
- Narrow evaporation notch
- Low heat-affected zone

Challenges

- Avoidance of fused-on parts, cracks, deflections, the formation of decomposition products and delamination of the coating

Technology alternatives

- Punching

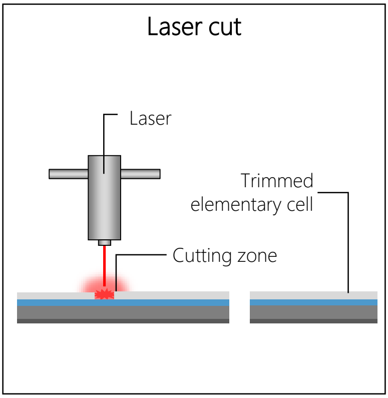
Transferability of competencies from the production of lithium-ion battery cells[1]

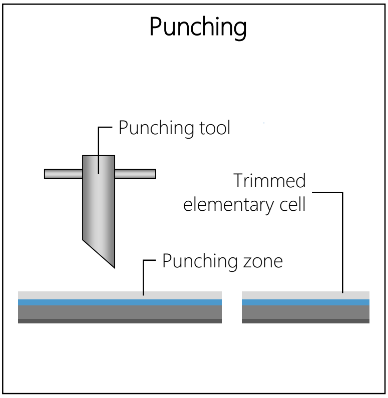
low 1 2 3 **4** 5 high

[1] Similar process step with adapted production technology

Sheet Separation

Cell assembly





Electrode & electrolyte production → Cell finishing

Process description

- After the layer lamination is complete, the elementary cells (smallest cell, consisting of anode, electrolyte and cathode) must be cut to be stacked in the next process step. This can be done by a laser cut or by punching.
- A burr-free cut can be produced by the correctly adjusted energy input of the laser into the layer composite. It is essential to ensure that the respective layer materials are not melted, which would lead to an electrical connection of the layers and thus to a short circuit.
- During punching, the film lies on a cutting die. The cutting process is carried out by pressing a cutting punch onto the film and into the cutting die.

Further information

- none

Process parameters & requirements

- Cutting speed
- Spot size
- Impulse energy and duration
- Impulse repetition rate
- Laser power or line energy
- Wavelength

Quality features

- Clean cut edge
- Narrow evaporation notch
- Low heat-affected zone
- Dimensions

Challenges

- Avoidance of deflections, cracks and delamination of the film
- Different laser settings due to the different materials

Technology alternatives

- none

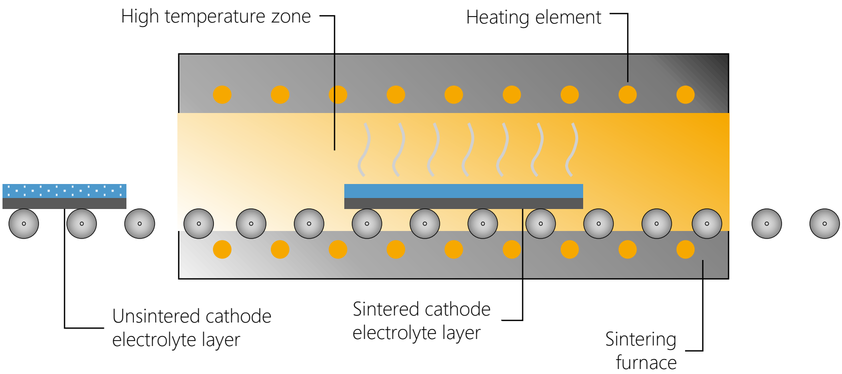
Transferability of competencies from the production of lithium-ion battery cells[1]

low 1 2 3 **4** 5 high

[1] Similar process step with adapted production technology

Sintering

Cell assembly



Process description

- Sintering is a process that produces the final strength and density of a component by heat treatment below the melting temperature. In this process, mass transport processes are thermally activated so that the particles of the component grow together.
- Sintering densifies the cathode and electrolyte layer. This can reduce the resistance between the electrolyte and the electrode interface.
- The cathode-electrolyte composite passes through a sintering furnace. The material is heated to a temperature below its melting point.

Further information

- Sintering occurs in an inert gas atmosphere or a vacuum to prevent environmental reactions.
- Sintering is particularly necessary for oxide-based solid-state electrolytes, which are not pressed after stacking, to achieve a sufficiently low interfacial resistance.
- Previously used binders or pore-forming agents are evaporated during the sintering process.

Process parameters & requirements

- Sintering time (usually several hours)
- Sintering temperature (1,000 – 2,000 °C for high-temperature sintering, 500 – 800 °C for low-temperature sintering)
- Sintering pressure (sintering at atmospheric pressure preferred)

Quality features

- Composite adhesion
- Porosity
- Grain size
- Avoidance of solvent residues

Challenges

- Different sintering kinetics and physical properties of the materials
- High energy input for high sintering temperatures

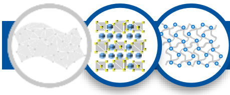
Technology alternatives

- Spark Plasma Sintering[1]
- Pulsed Laser Sintering

Transferability of competencies from the production of lithium-ion battery cells[2]	low	**1**	2	3	4	5	high

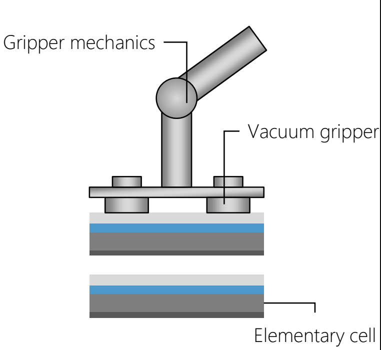
[1] Also known as "field-assisted sintering"
[2] New process step compared to the LIB

Stacking & Compression

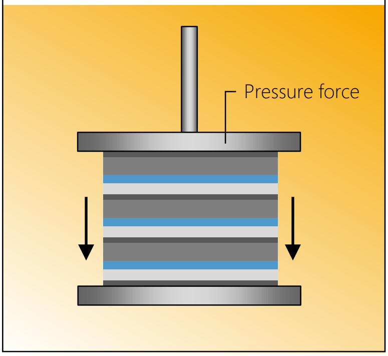


Cell assembly

Grasp & Stack



Pressing cell stacks



Electrode & electrolyte production → Cell finishing

Process description

- The elementary cells are positioned on top of each other with grippers. When selecting the gripping technique, it is essential to ensure that the surface is not damaged.
- When using sulfidic or polymeric solid electrolytes, the elementary cells are laminated together by applying pressure and heat. With sulfidic electrolytes, the grain boundary resistances in the electrolyte are reduced, the lithium-ion conductivity is increased and the interfacial resistance between the electrolyte and electrodes is reduced.

Further information

- The elementary cells can directly be stacked bipolarly. The resulting series connection of the cells enables a multiplied cell voltage and reduction of the packaging effort (number of collectors etc.), as only the outer collectors are required (also see “Contacting & Packaging”).
- Furthermore, no separator needs to be stacked additionally.

Process parameters & requirements

- Stacking speed (< 1 s/sheet)
- Positioning accuracy (< 300 µm)
- Temperature
- Pressure force

Quality features

- Positioning accuracy
- Damage-free stacking

Challenges

- Position detection and alignment of the sheets with a vacuum gripper
- Avoidance of short circuits during stacking

Technology alternatives

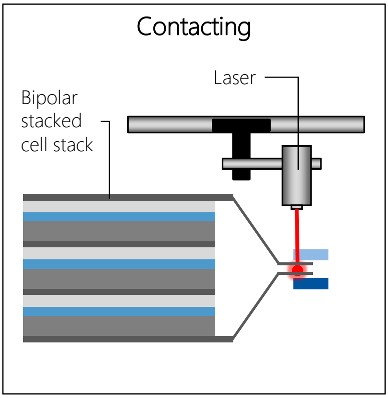
- Continuous stacking processes
- Winding the elementary cells[1]

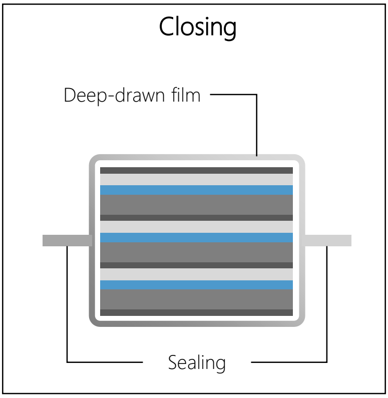
Transferability of competencies from the production of lithium-ion battery cells[2]	low	1	2	3	**4**	5	high

[1] Windings or “jelly rolls” are hardly possible due to the solid components of the solid-state battery and associated challenges.
[2] Similar process step with adapted production technology

Contacting & Packaging

Cell assembly





Electrode & electrolyte production → → → → → → Cell finishing

Process description

- The contacting can be done by laser beam welding. After contacting, the all-solid-state battery cell is placed in an electrically insulated, deep-drawn pouch bag and sealed to protect it from environmental influences.
- Foils in a metal-plastic composite are suitable packaging materials.
- The external current conductors must be electrically insulated and inserted into the foil. The packaging is completely sealed using impulse or contact seals.

Further information

- In the case of the bipolarly stacked cell, only the two outer current conductors need to be led to the outside after insertion into the housing and fixed via the sealing seam.
- The electrolyte filling that follows the sealing process in the production of lithium-ion batteries is not required when producing all-solid-state batteries.

Process parameters & requirements

- Welding speed
- Pulse frequency
- Laser power (< 4.000 W)
- Spot size
- Sealing time, temperature and pressure
- Deep-drawing depth of the pouch foil (< 10 mm)

Quality features

- Low mechanical and thermal stress during the welding processes
- Low contact resistance of the welds to the electrical contacts
- Strength and tightness of the sealed seam

Challenges

- Possible damage during welding
- Volume changes during loading and unloading

Technology alternatives

- Ultrasonic welding

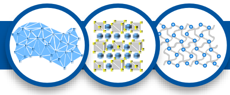
Transferability of competencies from the production of lithium-ion battery cells[1]

low 1 2 3 4 **5** high

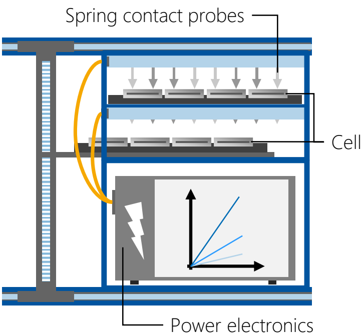
[1] Identical process step compared to the LIB

Formation & Aging

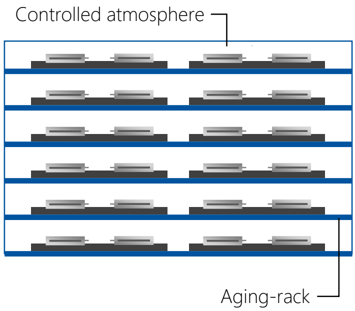
Cell finishing



Formation



Aging and EoL-Test



Electrode & electrolyte production → Cell assembly → →

Process description

- During formation, the battery cell is subjected to the first charging and discharging cycles. In the assembled state, an all-solid-state battery with a lithium metal anode is already charged.
- A boundary layer forms in the cell between the electrolyte and the electrodes. This layer significantly influences the ion conductivity and thus the performance of the cell.
- Aging is the final step in cell production and is used for quality assurance. The cells are stored in aging racks and/or towers.
- During aging, changes in cell performance are checked under controlled atmospheric conditions by regularly measuring the open-circuit voltage of the cell.

Further information

- Compared to the lithium-ion cell, less time and costs can be expected for the formation process.[1]
- In addition, a shorter aging time is expected, as stable properties of the cell are achieved more quickly due to the solid electrolyte.

Process parameters & requirements

- Defined C-rate for the first discharging and charging process and successive increase
- Current and voltage curve
- State of charge at the start of aging
- Aging duration
- Environmental condition (temperature etc.)

Quality features

- Formation of interface layers
- Temporal stability of interface layers
- Internal resistance of the cell
- Capacity
- Self-discharge rate

Challenges

- Location of the cells
- Type of contact
- Process temperature

Technology alternatives

- There are different procedures for the sequence and duration of high- and room-temperature aging depending on the cell manufacturer and cell chemistry.

Transferability of competencies from the production of lithium-ion battery cells[2]

low 1 2 3 4 **5** high

[1] Formation and aging are based on extensive experience which does not yet exist for all-solid-state batteries because they are not yet ready for series production. However, based on the material properties and interfaces, a time reduction is emerging.
[2] Identical process step compared to the LIB