PRESS RELEASE

From lab to manufacturing: Laser processes as enablers for industrial solid-state batteries

Solid-state batteries promise greater safety, higher energy density, and new degrees of freedom in cell design. Yet the path from laboratory cell to industrial production is challenging. Laser processes can overcome key hurdles and enable a breakthrough.

Lithium-ion batteries are the standard for electrical energy storage – from consumer electronics and electric mobility to stationary storage systems – and have undergone remarkable development in recent years.

However, the technology is reaching its physical limits. Energy density is growing only slowly, safety remains limited due to liquid electrolytes, and dependence on critical raw materials such as nickel, manganese, or cobalt is unresolved. Solid-state batteries are therefore considered the next generation of electrochemical storage. They promise higher energy densities thanks to lithium metal anodes, greater safety and a wider temperature window thanks to solid electrolytes, as well as new degrees of freedom in cell design.

Yet they have not reached industrial maturity. Materials such as lithium metal and sulfide-containing electrolytes require new process strategies, and manufacturing requires investment in specialized dry room or inert gas environments. Laser technology can make a decisive contribution, for example through selective sintering of solid electrolytes, targeted structuring of interfaces, and contact-free cutting of ductile metals. Thus, it could prove to be a key technology on the path from laboratory cell to industrial solid-state battery.

Potential and Applications of Solid-State Batteries

Numerous manufacturers are currently advancing the development of solid-state cells. Asian companies such as Toyota, BYD, Samsung SDI, and SVOLT have published ambitious schedules for pilot production starting in 2027. European car manufacturers such as Mercedes-Benz and Stellantis are also testing initial semi-solid-state concepts with partners, while Nissan is already building a pilot factory in Yokohama. These activities show that the technology is increasingly leaving the laboratory and moving toward industrial implementation.

"The key advantage of solid-state batteries lies in their intrinsic safety," explains physicist Stoyan Stoyanov from the cutting department at the Fraunhofer Institute for Laser Technology ILT. "Since they do not use liquid electrolytes, there is no risk of leakage or thermally induced fires. Additionally, the high mechanical stability of many solid electrolytes inhibits the formation of lithium dendrites, which are the main cause of internal short circuits in conventional cells."

Besides safety, higher energy density is the main driving force. Lithium metal anodes with a specific capacity of 3860 mAh g^{-1} outperform graphite anodes by far. Combined with thin, solid electrolytes, this enables advantages in range and weight, a decisive factor for electromobility and aviation.

The first fields of application are emerging where maximum safety and performance are crucial: in aerospace, motorsports, medical technology, and high-security data storage. Here, the higher energy density justifies the complex manufacturing process.

For the mass market, economic competitiveness remains limited for now. The production infrastructure is still being developed, and established lithium-ion systems continue to evolve in parallel.

"Solid-state batteries will exist alongside conventional lithium-ion cells for the foreseeable future and will primarily serve particularly demanding applications in the automotive industry, such as the luxury vehicle market," says Stoyanov.

Challenges in Manufacturing

As promising as the potential of solid-state batteries is, the hurdles to industrial implementation are just as great. Handling lithium metal anodes is particularly challenging: although the material is attractive due to its exceptionally high specific capacity, it proves to be extremely sensitive during processing. It reacts strongly with oxygen and moisture, easily forms passive layers, and can ignite under mechanical stress. Conventional cutting or rolling processes quickly reach their limits here.

Fundamental difficulties also arise on the solid electrolyte side. Oxide ceramic materials such as lithium lanthanum zirconate (LLZO) must be sintered at around 1200 °C. This often results in lithium losses and secondary phases, which reduce ion conductivity. Such losses are not only a technological problem but also an economic one, as they render expensive raw materials unusable. Although so-called sacrificial powders can partly compensate for these effects, the process remains complex and sensitive to even the smallest fluctuations.

"Another bottleneck is the interface between the electrolyte and the anode. High transition resistances reduce performance and increase the risk of inhomogeneities during lithium plating and stripping. Mastering this interface chemistry is the basis for stable and long-lasting cells," explains Florian Ribbeck from the High-Temperature Functionalization group at Fraunhofer ILT.

In addition to these material-specific aspects, the production conditions themselves pose a major challenge. Solid-state batteries require inert gas or dry room atmospheres throughout, which necessitate high investments in infrastructure. Initial analyses show that reject rates of up to 30 percent can occur during industrial ramp-up, resulting in losses amounting to millions per day.

Even with established lithium-ion lines, the high reject rate is an acute problem. This problem is exacerbated in solid-state cells, as there are currently no closed recycling paths for the materials, which are not yet standardized. Each defective prototype therefore means not only economic damage but also the loss of valuable raw materials. "Laser-based processes can help to increase process stability and avoid waste from the outset," says Ribbeck.

Laser Sintering of Solid Electrolytes

One research approach at Fraunhofer ILT involves the processing of oxide ceramic solid electrolytes such as LLZO. This material is considered particularly promising because it exhibits high electrochemical stability compared to lithium metal anodes and is less reactive to environmental conditions than sulfide-containing electrolytes.

"At Fraunhofer ILT, we are investigating how laser radiation can be used as a locally limited and highly dynamic energy source to densify LLZO layers in a targeted manner," explains Florian Ribbeck. "The advantage lies in rapid heating combined with controlled cooling. This reduces lithium losses and avoids temperature incompatibilities within the cell assembly."

Initial experiments show homogeneous densification, although cracking and delamination remain key research topics. In addition to LLZO, NASICON-type electrolytes such as lithium aluminum titanium phosphate (LATP) are being investigated, which have similar process requirements but different stability windows.

Laser Structuring for Improved Interfaces

In addition to compaction of the electrolyte layers, the quality of the interface with the lithium metal anode is crucial for the performance of solid-state cells. “High transition resistances often occur here, which limit the electrochemical behavior,” explains Tim Rörig from the Surface Structuring group at Fraunhofer ILT. “Additionally, the low wettability of ceramic surfaces makes homogeneous lithium deposition difficult.”

Rörig and Ribbeck are therefore investigating how the interfaces can be optimized through targeted laser structuring. Using ultrashort laser pulses in the femtosecond range, they introduce microstructures into the surface of the solid electrolyte. These structures increase the effective contact area and promote a more even distribution of current, which can potentially reduce the interfacial impedance. “We have shown that reproducible structures in the range of around 30 µm can be generated,” explains Rörig.

However, the results obtained so far also highlight the complexity of the interaction. While the structured surfaces showed improved wetting in individual cases, the overall resistance of the cell sometimes increased. The researchers suspect that both changes in the crystal structure and process-related defects play a role in this.

Using Raman spectroscopy and other analytical methods, the researchers are currently characterizing the structural changes in the crystal lattice after laser processing. At the same time, they are investigating targeted Li plating to better control contacting, as well as concepts for so-called “anodeless batteries,” in which the lithium is only deposited during the first charging process.

Laser Cutting of Lithium Metal Electrodes

Another focus at Fraunhofer ILT is on cutting lithium metal foils for use as anode material. “Lithium metal is considered a key component for the next generation of high-energy cells, but it poses considerable challenges for manufacturing technology,” says Stoyan Stoyanov. “The material is soft, highly adhesive, and extremely reactive. Conventional mechanical processes such as rotary knives or stamping quickly lead to smearing, sticking of the tools, and inhomogeneous cut edges.” Additionally, only linear cutting geometries can be achieved mechanically, which severely limits flexibility in cell layout. Laser technology opens up new possibilities. As a contactless and wear-free process, it enables precise cuts and allows for flexible contours.

However, both mechanical and laser-based processes require processing exclusively in sealed inert gas or dry room atmospheres. These are essential for the safe handling of lithium, but they also pose their own process engineering challenges. “Argon is particularly suitable because it prevents oxidation and thus enables uniform edges, but it is expensive," as Stoyanov explains. "Nitrogen is significantly cheaper, but it leads to the formation of lithium nitrides. Atmospheres containing water, on the other hand, promote oxides and hydroxides." Such reaction products increase the energy requirements of the process and can also impair the electrochemical properties of the electrode.

Research is ongoing into more cost-effective process atmospheres and better control of lithium surface reactions. "These approaches are still at an early stage. In our lab demonstrator, we therefore use pure argon with a dew point below –70 °C, although other atmospheres are technically feasible."

An additional challenge is to avoid particles and splashes that can occur during the laser process. These impair the surface quality and lead to defects in the subsequent cell composite. Stoyanov and his team are therefore developing process strategies to control ablation in a targeted manner and efficiently dissipate emissions.

Ultrashort pulse lasers, which operate with pulse durations in the picosecond range, are one option for obtaining high-quality cut edges that are free of critical burr formation and have a minimal heat-affected zone. The team is also investigating options that are technologically easier to integrate and economically attractive, such as the use of nanosecond lasers, which enable acceptable cutting quality at lower investment costs. At the same time, the researchers are working on concepts for integrating the laser processes into scalable production environments, for example with the aid of compact mini-environments that can be flushed with inert gas in a targeted manner.

Bridge to Industrial Implementation

The transfer of solid-state batteries from the laboratory to industrial production requires not only new materials, but above all robust processes. The production of lithium-ion cells offers a valuable reference point. Many process steps, from electrode production and cell assembly to finishing, are comparable in principle, although the requirements for solid-state cells are significantly higher.

Laser technologies are already well established in lithium-ion production. They are used in laser slitting, i.e., the precise longitudinal cutting of electrode foils, in laser drying to remove solvents quickly and energy-efficiently, and laser notching of current collectors. Much of this experience can be transferred to solid-state cells. However, the demands on precision, purity, and material stability are increasing significantly: even the smallest particles, defects, or chemical changes can impair the function of the cells.

“That’s why laser processes are becoming increasingly important,” believes Stoyanov. “Their contact-free, selective energy input enables high-precision machining that can be integrated into protected environments such as dry rooms or mini-environments. This makes the laser a tool that can be used to meet material requirements and take strict environmental conditions into account.”

In this way, the process chains developed in the laboratory can be transferred to an industrial logic. Where high scrap rates and long start-up times still dominate today, laser-based processes can make a decisive contribution to ensuring the scalability and cost-effectiveness of solid-state batteries.

Positioning of Fraunhofer ILT

The Fraunhofer Institute for Laser Technology ILT bundles its competencies along the entire value chain of the solid-state battery. The focus is on laser-based manufacturing steps that are crucial for both material development and later industrialization. These include laser sintering of solid electrolytes, laser structuring to optimize interfaces, laser cutting of lithium metal foils, as well as processes for contacting and integration into the cell composite.

While one group investigates the properties and limits of new electrolytes and anode materials, another team develops processes to handle these materials in a robust and scalable way. “This dual perspective allows us to build the bridge between laboratory demonstration and industrial implementation at an early stage,” summarizes Ribbeck.

Nevertheless, solid-state batteries will not replace established lithium-ion cells anytime soon, even though they open up new perspectives for applications that place the highest demands on safety and energy density. “Aerospace, medical technology, high-performance vehicles, or uninterruptible power supplies for data centers and hospitals are examples where the advantages of solid electrolytes justify the additional expense,” says Stoyan Stoyanov. In the medium to long term, falling production costs could also pave the way for entry into broader markets.

This presents a particular opportunity for Europe. While the mass market for lithium-ion cells is strongly dominated by Asian manufacturers, there is not yet an established industrial monopoly in the field of solid-state technology. Companies and research institutions can position themselves early on, help shape standards, and build new value chains.

Battery Management and Sensor Integration

The safety, longevity, and performance of batteries depend largely on battery management. Sensor integration and the use of AI offer transformative opportunities to meet these requirements. Researchers at Fraunhofer ILT print sensors just a few micrometers thick directly onto components. These smart sensors enable continuous monitoring of temperatures and forces, for example, or even chemical changes within the batteries. AI-supported algorithms analyze the large amounts of data in real time and make predictions about the service life of the cells.

These systems also make it possible to dynamically adjust processes during production, for example by optimizing temperature profiles during cell assembly or adjusting laser welding parameters.

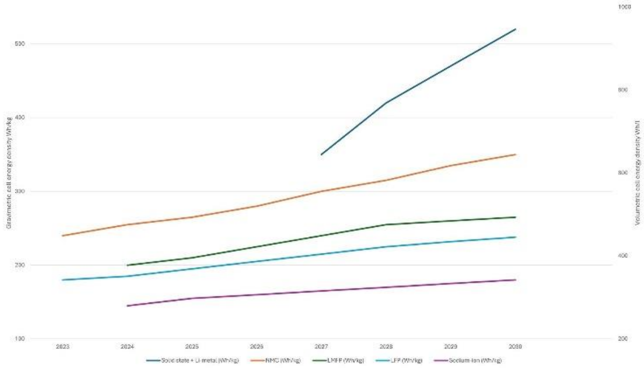

Image 1: Development of gravimetric (Wh/kg) and volumetric (Wh/l) cell energy density until 2030 for different battery types: Solid-state cells with lithium metal anodes achieve the highest values, while NMC, LMFP, and LFP lie lower; sodium-ion remains at a lower level. © Fraunhofer ILT, Aachen, Germany.

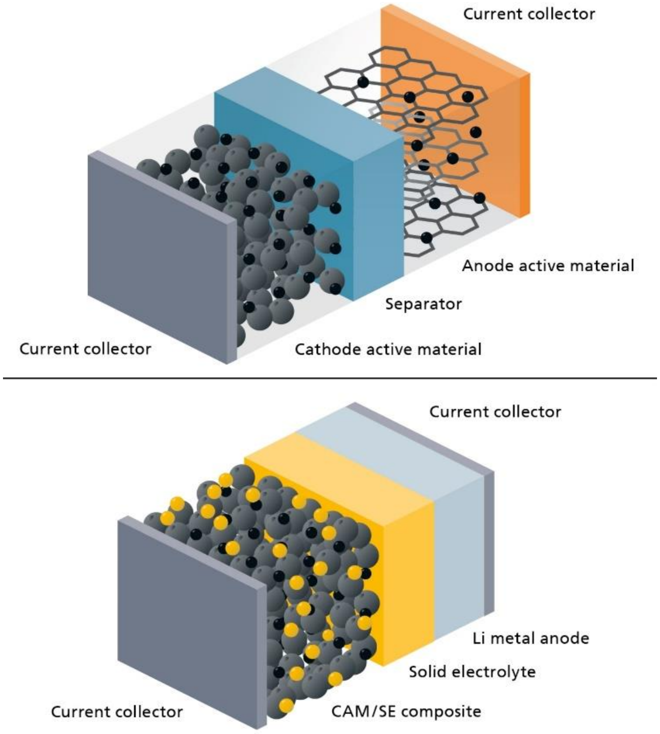

Image 2:
Schematic cell structure comparison. On the top, a conventional lithium-ion cell with liquid electrolyte and separator between cathode and anode material; on the bottom, a solid-state cell with solid electrolyte and lithium metal anode.
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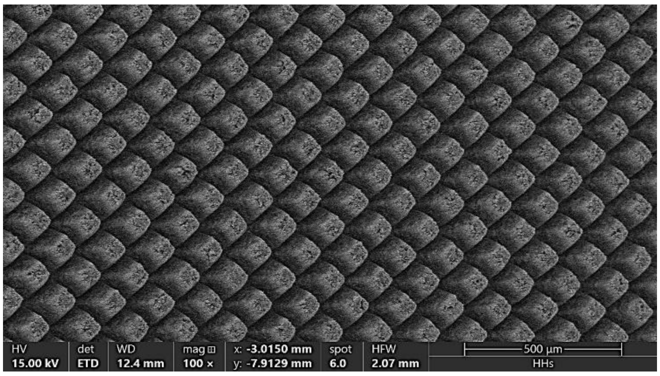

Image 3:
REM image of a microstructure generated by an ultrashort pulse laser on the surface of a solid electrolyte. The periodic structure increases the effective contact area, improves current distribution, and can reduce the interfacial impedance between the electrolyte and the lithium metal anode.
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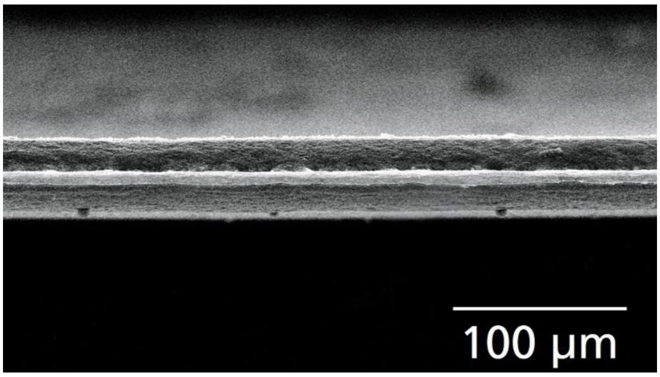

Image 4:
REM image of the cut edge of a laser-cut lithium metal anode. The laser process produces a uniform, virtually burr-free edge with minimal heat-affected zone and no mechanical deformation of the reactive metal.
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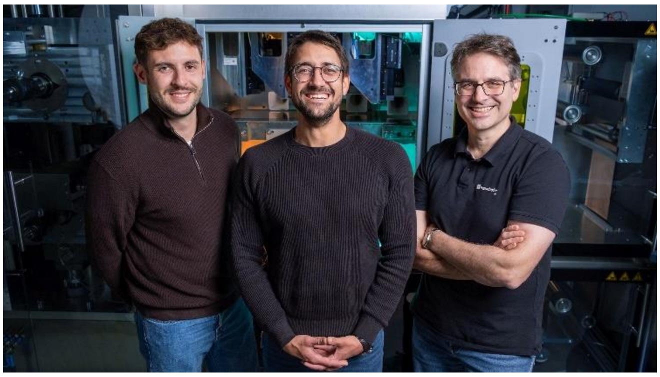

Image 5:
Researchers at Fraunhofer ILT: Tim Rörig, Florian Ribbeck, and Stoyan Stoyanov (from left) are developing laser-based processes for manufacturing solid-state batteries, including laser structuring of solid electrolytes and laser cutting of lithium metal anodes.
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