

The Process Variability in Battery Manufacturing, A Overview and Further Directions

Abstract—Battery storage was used in many places involving starting engines, portable devices etc., lithium-based batteries for a long time. Among all the batteries, lithium-based batteries have been widely concerned for its significant advantages such as high gravimetric, high volumetric, high cycle life, high energy efficiency and so on. As a result, Lithium-based batteries have been considered as the most promising storage battery compared to NiCd and NiMH batteries. As a storage container for renewable energy sources such as wind and solar, lithium-ion batteries reduce reliance on fossil fuels. Therefore, how to reduce the cost undoubtedly becomes an inevitable problem to develop renewable energy. On the one hand, PV industry adopt practices exist in the semiconductor manufacturing to reduce cost. On the other hand, the surface transportation sector is creating a huge market for batteries that actively participate in drive, which increase the demand for batteries. This research project will provide an overview of process variability in battery manufacturing and provide other manufacturing directions that can provide further cost reduction of manufacturing of Li-ion and solid-state batteries.

Index Terms—Battery storage, Lithium-based battery, solid-state manufacturing.

I. INTRODUCTION

Solid-state lithium-ion batteries, or simply solid-state lithium batteries, are lithium-ion batteries in which all battery units, including the positive and negative electrodes and the electrolyte, are made of solid materials. They have been developed since the 1920s. In terms of construction, solid-state lithium batteries are simpler than traditional lithium-ion batteries[1]-[3]. The solid electrolyte not only conducts lithium ions, but also serves as a separator, as shown in Figure.1. Therefore, in solid-state lithium batteries, there is no need to use electrolyte, electrolyte salts, separators, adhesives such as polyvinylidene fluoride, etc., greatly simplifying the construction process of the battery. The working principle of solid-state lithium batteries is similar to that of liquid electrolyte lithium-ion batteries. During charging, lithium ions in the positive electrode are detached from the lattice of the active material, migrate to the negative electrode through the solid electrolyte, and electrons migrate to the negative electrode through the external circuit. The two combine at the negative electrode to form lithium atoms, alloy or embed into the negative electrode material. The discharge process is the opposite of the charging process, where electrons drive electronic devices through the external circuit[4].

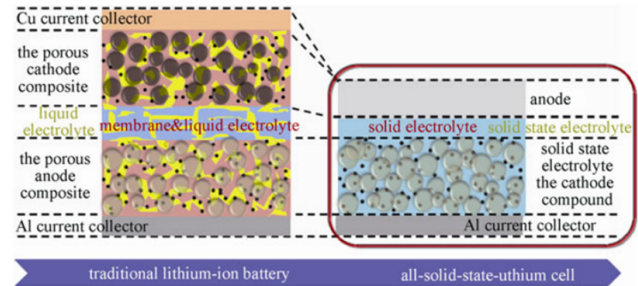


Fig. 1. Schematic illustration of an all-solid-state lithium cell

The manufacturing of lithium-ion batteries involves several steps that vary depending on the manufacturer. The processing steps also depend on the chosen chemical composition. After the prototype design, the desired cathode, anode, and other chemicals are selected and arranged to form the battery[5]. Depending on the selection and arrangement, the potential and performance of the battery will be different. Common steps in the manufacturing process include preparing the anode and cathode and applying chemicals to remove solvents. The electrode, electrolyte, binder, separator materials are assembled to form a complete battery. Finally, the battery is tested, graded, and packaged into a complete battery pack, which may contain only one or several batteries. From the manufacturer's perspective, the goal is to minimize the variability of each step and not deviate significantly from the target numbers when obtaining the final product[6]. Manufacturers need to improve battery efficiency, control component variability, and improve manufacturing capabilities through the battery structure in the manufacturing process. In addition, quality control can be achieved in the production process, and manufacturing efficiency can be improved and supply chain costs can be reduced through physical and information means.

In December 2020, the US Department of Energy released a report titled "Energy Storage Grand Challenge Roadmap", which advances the development of energy storage in the United States through the "three major technologies" and "five major paths". The three major technology directions in energy storage include: bidirectional power storage technology, chemical energy storage and thermal energy storage technology, flexibility power sources and controllable loads[7]. Among them, in bidirectional power storage technology, lithium-ion batteries, sodium-based (including sodium-ion, sodium-metal batteries), lead-acid batteries, zinc-based secondary batteries, and other metal (magnesium, aluminum) system batteries, flow batteries, rechargeable fuel cells, and electrochemical capac-

M. Shell was with the Department of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA, 30332 USA e-mail: (see <http://www.michaelshell.org/contact.html>).

J. Doe and J. Doe are with Anonymous University.

Manuscript received April 19, 2005; revised August 26, 2015.

itors, including electrochemical energy storage technologies. It is required that the average cost of long-term fixed energy storage be reduced to \$0.05/kWh, a 90% reduction compared to 2020; the cost of electric vehicle battery packs for a 300-mile range be reduced to \$80/kWh, a 44% reduction compared to the current \$143/kWh for lithium-ion batteries.

II. MAIN RESULTS

A. Problem Setup

All manufacturing processes have inherent statistical variability, including the electrochemical and solid-state cells that make up a complete battery. Precise measurements are necessary for control purposes before any corrections can be made. Without measurements, unidentified problems cannot be fixed, and control cannot be meaningful[8]. However, the measurement system that works best for a specific process will differ. Therefore, the measurement scheme, data collection, analysis, and feedback must be customized for each process. A useful measure of this customization is expressed in terms of the process-to-tolerance (P/T) ratio. The P/T ratio is defined as the ratio between the process variability and the tolerance limit:

$$\frac{P}{T} = \frac{6\sigma_{\text{precision}}}{\lim_{\text{upper}} - \lim_{\text{lower}}} \quad (1)$$

where $\sigma_{\text{precision}}$ is square root of sum of repeatability and reproducibility of measurement, \lim_{upper} and \lim_{lower} are upper and lower limits of tolerance, respectively.

In a study conducted on solid-state electrolyte for Li-ion cells, the researchers found that variation in the cooling rate resulted in a variation of ionic conductivity. Therefore, the thermal process must be precisely controlled to maintain a consistent cooling rate in all batches. Improvements in battery technology can come from utilizing the insights gained from the equivalent circuit model of the battery.

In this article, we will provide a more detailed explanation of the various aspects related to the manufacture of lithium batteries. A single electrochemical or solid-state cell is commonly referred to as a "battery", while a collection of these cells is known as a "battery pack". The latter often includes a battery management system (BMS) that comprises sensors, controllers, processing units, and other components to optimize the performance and lifespan of the battery.

The manufacture of lithium batteries typically involves multiple steps, which can vary depending on the manufacturer and the specific chemical composition. Once the prototype design has been finalized, the cathode, anode, and other chemical components are selected based on the desired specifications for the battery. The potential and performance of the battery can be altered depending on the choice and arrangement of these components.

The preparation of the anode and cathode is an essential step in the manufacturing process. The chemicals are applied to the electrodes to create a coating, and drying steps are usually required to remove any solvents. Next, the various materials including the electrode, electrolyte, adhesive, separator, etc., are assembled to form a complete battery.

Once the battery is assembled, it is tested, graded, and packaged into a complete battery pack. The manufacturer aims to minimize variability during each step of the manufacturing process and ensure that the final product meets the target specifications. Improving battery efficiency, controlling component variability, and enhancing manufacturing capabilities are essential aspects that need to be considered during the production process.

Quality control is another critical factor in the manufacturing process. It can be achieved through various physical and informational means, such as conducting rigorous testing procedures and implementing comprehensive data analysis tools. These measures can help improve manufacturing efficiency and reduce supply chain costs.

Overall, the manufacturing of lithium batteries is a complex process that involves multiple steps and considerations. By carefully managing each step of the process, manufacturers can create high-quality batteries that meet the required specifications and performance standards.

B. Modify Process Mechanism

Solid-state lithium batteries have garnered significant interest due to their potential for higher energy densities and improved safety compared to traditional liquid electrolyte batteries. The main focus of improving the performance of solid-state lithium batteries is on the formation technology of the electrolyte, and controlling the uniformity of the electrolyte film is a crucial factor in battery manufacturing.

1) *Optimization methods for electrolytes of different battery types:*

The polymer electrolyte layer can be prepared using either dry or wet methods, and the cell assembly is achieved through roll-to-roll lamination between the electrode and electrolyte. Both methods are mature and easy to scale up for the production of large cells. However, these methods have some disadvantages, such as difficulty in controlling film uniformity and incompatibility with high-voltage positive electrode materials, leading to low energy density and limited operating temperature.

Improving the preparation of positive electrode and electrolyte materials involves optimizing the mechanical properties of the preparation equipment, such as uniformly extruding relevant substances, adjusting pressure and preparation speed, reducing the tension of the electrolyte coating, and fully laminating.

Oxide solid electrolytes have relatively high ionic conductivity and stable chemical properties, making them suitable for large-scale production and application. However, conventional preparation methods require high-temperature sintering, which consumes a lot of energy and has high production costs. To overcome this, new technologies have been proposed, such as using water solutions for low-temperature sintering, developing new oxide solid electrolyte powder materials, and controlling the temperature and uniformity of finished products through material pre-processing.

Sulfide solid electrolytes have ultra-high ionic conductivity and good mechanical properties, making it possible to construct a fully solid-state lithium battery without any electrolyte.

However, their air stability is poor, the synthesis process is complicated, and the production rate is low, which greatly hinders their large-scale application. The main focus of research in this area is to mass-produce sulfide solid electrolytes to improve lithium battery performance and form the next generation of industrial solid-state lithium-ion battery industry chains.

In summary, the formation technology of the electrolyte and increasing the energy density of the solid-state electrolyte while controlling the uniformity of the electrolyte film are critical factors in improving the performance of solid-state lithium batteries. Researchers are actively exploring new technologies and materials to overcome the limitations of current manufacturing methods and accelerate the development of solid-state lithium batteries.

2) Optimization methods for interface production:

For inorganic all-solid-state lithium batteries, the interface is crucial to the overall battery performance. In all-solid-state lithium batteries with thio-LISICON (lithium ion superionic conductors) sulfide materials as electrolytes, although the room temperature ionic conductivity of the solid electrolyte can reach 2.2×10^{-3} S/cm, the capacity of the entire battery is still not high. In-depth research has shown that the most critical factor that determines the capacity and high-rate performance of the entire battery is the interface between the oxide cathode and the sulfide solid electrolyte. In all-solid-state lithium secondary batteries with LiCoO₂ as the cathode and thio-LISICON as the electrolyte, the cause of the difference in high-rate capacity of the cathode material is the high-resistance space charge layer formed at the LiCoO₂/sulfide electrolyte interface. The reason is that oxide cathodes, such as LiMO₂ (M=Co, Ni, etc.), have relatively high electronic conductivity. When they are in close contact with pure ionically conductive sulfide electrolytes, a high-resistance interface layer, i.e., a space charge layer, will be generated at the interface, which will have adverse effects on the performance of the battery and electrode materials. Because the interaction force between oxygen and lithium ions is much stronger than that between sulfur and lithium ions, there is a significant difference in the lithium ion electrochemistry between oxides and sulfides, as shown in Figure 8. When the oxide cathode belongs to a mixed conductor that has both ionic and electronic conductivity, a space charge layer will be generated at the electrode/electrolyte interface, and a Schottky-type space charge layer will be formed at the electrolyte end of the interface, as shown by the red box in 2. In order to obtain the best lithium ion conductivity, the chemical composition and structure of the solid electrolyte have been rigorously optimized. When the composition changes, the lithium-deficient layer will be formed in the space charge layer region of the sulfide electrolyte end at the interface, leading to a significant reduction in ionic conductivity and the formation of a high-resistance oxide cathode/electrolyte interface. The formation of a high-resistance interface layer will greatly reduce the lithium ion migration kinetics at the interface. Therefore, understanding and improving the interface between the oxide cathode and the sulfide electrolyte are essential for improving the electrochemical performance of current all-solid-state

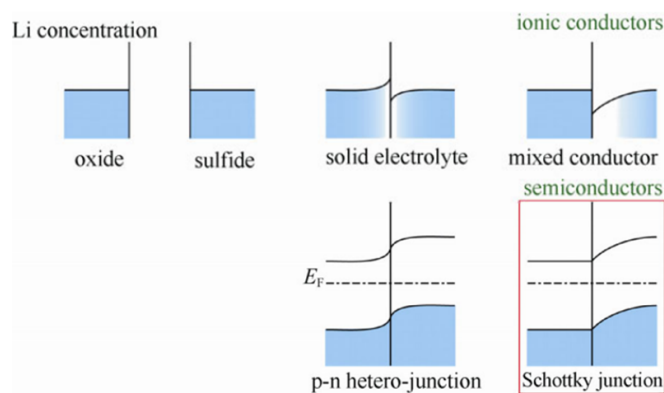


Fig. 2. The diagram of potential change in the hetero junction between an ionic conductor

lithium batteries. Interface problems mainly involve five aspects: interfacial material interaction, interfacial reaction mechanism and interfacial product identification, interfacial dynamics, interfacial structure, and interfacial modification. The properties of the interface have a significant impact on the energy storage efficiency, cycling performance, rate characteristics, self-discharge, and safety of the battery. At the same time, the development of advanced in situ and atomic-level recognition capabilities for complex interface processes is becoming increasingly important and urgent.

3) Advanced technology development and its data indicators:

Albemarle Corporation, one of the world's largest producers of lithium carbonate, announced in 2021 its acquisition of China's Tianyuan New Energy Materials Co., Ltd. The acquisition will expand its lithium production capacity and is currently in the trial operation phase. The company has a designed annual conversion capacity of 25,000 tons and is expected to begin commercial production in the first half of 2022. Additionally, Albemarle Corporation has signed a joint development agreement with 6K, a professional 3D printing material developer in the United States, primarily for the production of new lithium-ion battery materials. This collaboration will be achieved through 6K's UniMelt microwave plasma system patent technology, a sustainable material production platform for industrial-grade powders that is expected to reduce CO₂ emissions by 70%, water consumption by 90%, completely eliminate wastewater generation, and reduce factory space by 50%.

Sila Nano, a new generation battery material start-up company in California, has raised \$590 million in series F financing, which will be used to support the construction of a silicon-based anode material production base in North America. Silicon-based anode materials are used in the production of new generation batteries and have the characteristics of long service life, ultra-low expansion rate, and high energy density. These materials can increase the energy density of lithium batteries by 20%, or even up to 40%. The company is currently collaborating with BMW, ATL, and other enterprises to develop the next generation of batteries, with plans to achieve mass production of its silicon-based anode materials

in 2024.

Redwood, the largest lithium-ion battery recycling company in North America, is dedicated to inventing and promoting the technology to recover and reuse materials from lithium-ion batteries. The company announced a new investment plan of hundreds of millions of dollars to expand its battery recycling production lines, including the construction of a cathode material factory in Nevada. By the end of 2025, the new Redwood factory will have an annual production capacity of cathode materials of 100 GWh, enough for about 1.3 million long-distance vehicles, and by 2030, the annual production capacity of the factory will increase to 500 GWh.

C. Synthesis of the Raw Materials with Uniformity, Supply Chain and Industrial Internet of Things

The manufacturing process of lithium batteries is a complex and sensitive process, and the quality of the battery can be significantly impacted by various factors. To ensure high-quality products, precise and automated equipment is necessary to monitor the manufacturing process. A new manufacturing model is proposed in this article, based on the concept of LLoT, which stands for "smart + digital + information-based enterprise."

The LLoT model comprises three hierarchical levels: the enterprise level, workshop level, and execution level. Compared to traditional manufacturing models, this new model can shorten product development cycles and enhance responsiveness to customer needs. From a quality perspective, this model enables faster analysis and shorter handling times for after-sales service. The Manufacturing Execution System (MES) is used to trace the product and identify the production batch and critical parameters in the manufacturing process, resulting in faster problem-solving.

The digital workshop layer is based on MES, which enables comprehensive control of the production process. The design combines battery structure and thermal performance simulation systems (ANSYS), MES, and Enterprise Resource Planning (ERP) software to achieve digital three-dimensional product design and process simulation, process flow design and digital modeling, and establish a product data management system. Real-time data collection and visualization are used to enable seamless collaboration among ANSYS, MES, and ERP systems, facilitating automatic intelligent operation from product design to manufacturing. The execution layer focuses

(IoT). The production process is modeled, and core intelligent manufacturing equipment is developed based on the characteristics of the process equipment to enable information exchange and data collection between the control center, production equipment, and IoT. Industrial Ethernet technology is used, and an online fault diagnosis and analysis system is applied to establish the Profibus network, connecting the PLC on the production line.

Data on equipment operation status is collected, automatically analyzed and diagnosed, and recorded in the equipment archive database. Preventive indicators are established based on this analysis to achieve predictive maintenance of the equipment. Digital models are created to analyze the lifecycle of critical components, evaluate the types and quantities of spare parts, and determine safety stocks to ensure the effective continuity of production. This enables a more accurate assessment of the types and quantities of vulnerable parts in the equipment, resulting in more precise maintenance costs and more effective use of funds. The resulting improvement in yield due to defect reduction will help reduce the cost of ownership (COO).

In summary, the LLoT model proposed in this article provides a comprehensive and effective solution to enhance the performance and quality of lithium battery manufacturing. The model leverages the latest technological advancements in digitalization, automation, and the Internet of Things to create a smart and information-based enterprise that can produce high-quality lithium batteries.

III. CONCLUSION

As the demand for high-energy-density and safe batteries continues to rise, all-solid-state lithium metal batteries have emerged as a promising solution. However, their production process poses several challenges that need to be addressed to achieve high-performance and mass production. The focus of future production processes for all-solid-state lithium metal batteries should be on improving the electrolyte membrane conductivity and mechanical strength, increasing the positive electrode active material content and surface capacity, and developing efficient mass production processes.

Intelligent manufacturing can play a crucial role in addressing these challenges by addressing issues such as dry electrode technology and equipment, solid electrolyte membrane mass production technology and equipment, thermal composite technology and equipment, and assembly and testing equipment. By integrating intelligent systems and equipment development with information technology, advanced manufacturing technology, and mode research and development, the new digitalized workshop model can improve product quality and reduce production costs.

The smooth implementation of this new intelligent manufacturing model will form a paradigm shift in the dynamic lithium battery production and manufacturing industry. It will enable faster development and prototyping of new batteries, shorten production cycles, and reduce production costs while improving product quality and reliability. As a result, it will create a more efficient and sustainable manufacturing process

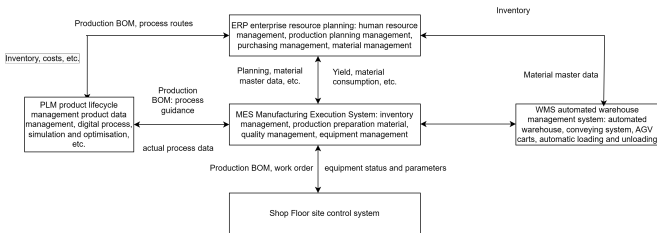


Fig. 3. Overall planning and hierarchy of the new model of intelligent manufacturing

on intelligent production equipment and the Internet of Things

for all-solid-state lithium metal batteries that can meet the growing demand for high-performance and safe energy storage solutions.

REFERENCES

- [1] P. G. Bruce, S. A. Freunberger, L. J. Hardwick, and J.-M. Tarascon, "Li-O₂ and Li-S batteries with high energy storage," *Nat. Mater.*, vol. 11, no. 1, pp. 19–29, Jan. 2012.
- [2] Y. Xia, Y. Sun, and X. S. Zhao, "Advanced sodium-ion batteries: beyond intercalation chemistry," *Adv. Energy Mater.*, vol. 8, no. 6, 1703139, Feb. 2018.
- [3] Z. Chen, Y. Wang, and Y. Cui, "Sodium-ion batteries: fundamentals and applications," *Small*, vol. 16, no. 5, 1907059, Feb. 2020.
- [4] Y. Zhang, J. Dong, X. Wang, and J. Xie, "Recent advances in magnesium ion batteries," *Mater. Today*, vol. 21, no. 7, pp. 705–724, Sep. 2018.
- [5] M. Armand and J.-M. Tarascon, "Building better batteries," *Nature*, vol. 451, no. 7179, pp. 652–657, Feb. 2018.
- [6] M. Armand, "Rechargeable lithium batteries: a primer," *Mater. Today*, vol. 7, no. 12, pp. 20–27, Dec. 2014.
- [7] S. P. Ong, V. L. Chevrier, G. Hautier, A. Jain, C. Moore, and G. Ceder, "Voltage, stability and diffusion barrier differences between sodium-ion and lithium-ion intercalation materials," *Energy Environ. Sci.*, vol. 4, no. 9, pp. 3680–3688, Jul. 2022.
- [8] M. L. Trudeau, S. E. Doris, S. L. Gollledge, and G. P. Grey, "Characterization of intercalation compounds and electrochemical extraction of sodium from NaTi₂(PO₄)₃," *J. Electrochem. Soc.*, vol. 152, no. 12, A2406-A2411, Oct. 2015.
- [9] Y. Li, Y. Lu, X. Zhao, and L. Li, "Ionic liquid electrolytes for electrochemical energy storage devices," *Chem. Soc. Rev.*, vol. 46, no. 6, pp. 1590–1604, Jan. 2017.
- [10] Noriaki K., Kenji H., Yuichiro Y., et al. "A lithium superionic conductor," *Nat. Mater.*, 2021, 10(9)
- [11] Keiichi M., Akitoshi H., Masahiro T. "Crystallization process for superionic Li₇P₃S₁₁ glass-ceramic electrolytes," *J. Am. Ceram. Soc.*, 2020, 94(6): 1779-1783.
- [12] Zhu X. J., Shen O. C., Xu X. X., et al. "Direct observation of lithium-ion transport under an electrical field in Li_xCoO₂ nanograins," *Sci. Rep.*, 2013, 3: 1-8
- [13] Ohta N., Takada K., Zhang L. Q., Ma R. Z., Osada M., Sasaki T. "Enhancement of the high-rate capability of solid-state lithium batteries by nanoscale interfacial modification," *Adv. Mater.*, 2016, 18(17): 2226-2229.
- [14] Maier J. "Nanoionics: Ion transport and electrochemical storage in confined systems," *Nat. Mater.*, 2005, 4(11): 805-815.
- [15] Xu X. X., Takada K., Fukuda K., et al. "Tantalum oxide nanomesh as self-standing one nanometre thick electrolyte," *Energy Environ. Sci.*, 2021, 4(9): 3509-3512.
- [16] Armand M., Tarascon J. M. "Building better batteries," *Nature*, 2008, 451: 652-657.
- [17] Croce F., Appetecchi G. B., Persi L., Scrosati B. "Nanocomposite polymer electrolytes for lithium batteries," *Nature*, 2008, 394: 456-458.
- [18] Sasaki T., Watanabe M., Hashizume H., Yamada H., Nakazawa H. "Macromolecule-like aspects for a colloidal suspension of an exfoliated titanate. pairwise association of nanosheets and dynamic reassembling process initiated from it," *J. Am.*