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ADVANCED MANUFACTURING PROCESSES FOR HIGH-PERFORMANCE LITHIUM-ION BATTERY PACK PRODUCTION: A STUDY OF MAXVOLT ENERGY IN 2W & 3W

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ABSTRACT

The rapid rise of electric mobility in India, especially in terms of two-wheeler and three-wheeler electric vehicles, has led to a surge in demand for lithium-ion battery pack manufacturing systems. This paper aims to provide a comprehensive study of advanced manufacturing techniques and intelligent system implementation for high-performance battery pack manufacturing. Emphasis is given to Maxvolt Industries. Various phases of battery manufacturing, including cell selection and grading, series-parallel combination, busbar welding, battery management system implementation, and thermal management, are discussed in detail. Industry 4.0 technologies, including IoT-based monitoring, data-driven quality control, and predictive maintenance, are discussed in relation to battery manufacturing. A comparative study of battery pack manufacturing for two-wheeler and three-wheeler vehicles is provided, including factors such as battery capacity, thermal management, mechanical strength, and system complexity. Various challenges associated with battery manufacturing, including safety, scalability, and cost, are identified, and possible solutions are provided.

This study aims to provide valuable insights for enhancing battery pack reliability, thus contributing to the rapid adoption of electric vehicles in emerging economies.

Keywords: Lithium-Ion Battery, Battery Pack Manufacturing, Battery Management System (BMS), Industry 4.0, Assembly Production, ESS

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1. INTRODUCTION

The rapid rate of electrification in transportation, especially in developing economies such as India, has significantly increased the pace of demand for reliable, cost-effective and high-performance energy storage solutions. Among all forms of electric vehicles are dominating the market in terms of adoption, driven by factors such as cost-effectiveness, efficiency, and suitability for urban and semi-urban mobility. At the core of this revolution is the lithium-ion battery pack, which is used as a source of power and is a crucial factor in determining the overall performance, safety, and cost of electric vehicles [1].

India's electric vehicle market has shown rapid growth over the last five years. According to industry estimates, electric two-wheelers contributed approximately 56–60% of total EV sales in India in 2025, while electric three-wheelers accounted for nearly 32–35% of commercial EV adoption. Government initiatives such as FAME-II, PLI schemes for ACC battery manufacturing, and increasing fuel prices have accelerated demand for lithium-ion battery packs. The Indian lithium-ion battery market is projected to grow at a CAGR exceeding 18% between 2025 and 2030, driven primarily by electric mobility and energy storage applications.

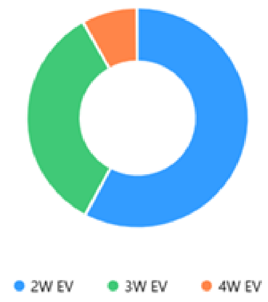

Figure 1: Indian EV Market Share by Vehicle Type (2025)

In this context, indigenous companies such as Maxvolt Energy Industries Ltd. are seen to be contributing significantly towards enhancing supply chain strength in India and fulfilling the "Make in India" vision. However, this transition from conventional battery assembly to advanced, high-speed, and intelligent battery manufacturing is associated with a number of technical and operational challenges [2]. The present manufacturing techniques in battery pack construction have evolved beyond mechanical construction alone and involve a sophisticated integration of various components like electrochemical, thermal, electrical, and structural subsystems. Advanced manufacturing techniques like automated cell sorting, precise welding techniques like laser or ultrasonic welding, quality monitoring in real-time and digitalization or traceability of manufacturing processes are increasingly being adopted in the construction of battery packs. Moreover, the integration of Industry 4.0 technologies like the data analysis and automatic production lines also plays a vital role in the construction of battery packs [3].

The other important aspect to be considered in the construction of battery packs is the differentiation in design requirements between 2W and 3W applications. While the design requirements for 2W battery packs are based on compact design, lightweight construction and cost-effectiveness, the design requirements for 3W battery packs are based on higher energy density, better thermal management and mechanical strength due to their usage in the commercial sector. This paper aims to present a detailed analysis of the advanced manufacturing processes and digital system integration in the development of lithium-ion battery packs, specifically with reference to Maxvolt Industries. Furthermore, the paper aims to present a comparative analysis of 2W and 3W battery pack development, including the design considerations and development processes for the development of battery packs in the electric mobility landscape [4].

Table 1: Comparison Between 2W and 3W Battery Packs

Parameter	2W Battery Pack	3W Battery Pack
Typical Voltage	48–72 V	48–96 V
Capacity Range	20–40 Ah	80–200 Ah
Cooling Method	Passive/Active Air Cooling	Active Air/Liquid Cooling
Weight	Lightweight	Heavy-duty
Application	Personal Mobility	Commercial Mobility
Thermal Load	Moderate	High
Manufacturing Complexity	Medium	High

2. ADVANCED ASSEMBLY PROCESSES FOR CELL TO BATTERY PACK

The process of manufacturing high-performance lithium-ion battery packs requires a series of specific and regulated manufacturing processes. These processes ensure the electrical, mechanical, and safety characteristics of the final battery system for use in electric vehicles, energy storage systems, and other applications. The battery manufacturing plants now use automated equipment, precision devices and inspection tools to ensure consistency and quality. These processes include cell sorting and grading, module assembly, joining processes, BMS integration, testing and inspection, pack assembly, and final validation.

2.1. Cell Sorting & Grading

Cell sorting and grading is a process of identifying and grouping the cells with similar parameters and characteristics so that they have similar performance during operation cycles. Cell sorting is the most critical step to assure safety of the battery pack. Even though cells may originate from the same manufacturing batch, slight variations in capacity, internal resistance, open-circuit voltage (OCV), and self-discharge characteristics naturally occur. If unmatched cells are assembled together, these differences can cause imbalance during charging and discharging, leading to overheating, reduced lifespan, and safety risks [5]. To prevent this, automated sorting machines are used to sort the cells based on their electrical properties. Each cell is tested with the use of OCV testers, internal resistance testers, and capacity grading systems.

Data is then processed from the tests conducted on the cells with the use of automatic controlled sorting machines. Some of the machinery used at this stage includes: Automatic battery cell sorting machine, Internal resistance testers, Voltage measurement systems, Barcode scanners.

Figure 2: - Cylindrical cell grading Machine

The figure 2 represents a cell grading machine used in LIB manufacturing. This machine tests and grades individual battery cells based on their voltage, capacity, internal resistance, charge-discharge characteristics and other essential parameters. A number of battery cells are placed in the racks of the machine, which then tests the cells by discharging them. Depending on the results, the cells are graded and grouped into similar ones, ensuring that they are uniform in their characteristics while being used in the construction of battery packs.

Figure 3: Cell sorting with IR automatic machine

Figure 3 shows a cell sorting machine used in lithium-ion battery production. The machine is used in the process of sorting lithium-ion cells based on different parameters. After obtaining the test results, different types of lithium-ion cells can be sorted based on their similar performance characteristics.

2.2. Automated Module Assembly

Once cells are sorted, they are arranged into modules according to the required series–parallel configuration. Module assembly begins with mechanical placement of cells into holders or frames that maintain spacing and alignment. Insulating materials such as fish paper, mica sheets, or polymer separators are added to prevent short circuits and enhance electrical isolation. Cells are configured electrically to meet voltage and capacity requirements i.e. series connections increase voltage while parallel connections increase capacity [6]. Modern battery factories rely on robotic assembly systems and automated stacking machines to ensure high accuracy and repeatability. Cells are transported using conveyor systems and positioned into module fixtures where alignment tools maintain correct spacing between cells [7].

2.3. Advance Joining Technique

Connections between the electrical cells of the battery are facilitated through advanced joining techniques. These connections play a critical role in the formation of series and parallel connections that define the voltage and capacity of the battery module. High-precision joining welding techniques, including: Laser welding, Ultrasonic welding, Resistance spot welding [8]. The laser welding machine is the most common welding machine used for welding the copper or aluminum busbar and the battery terminals. Laser welding provides precision, a limited heat affected zone, and a strong electrical connection. Laser welding machines use computer-controlled laser beams to produce welds. Proper welding parameters such as laser power, pulse duration, and penetration depth are optimized to avoid weak joints or overheating of cell terminals. Automated welding systems ensure repeatability and high production speed. Poor welding can increase electrical resistance, generate localized heating, and reduce overall pack efficiency. Therefore, weld quality inspection using visual analysis or non-destructive testing is essential to guarantee long-term reliability [9].

Figure 4: Automatic laser wielding

The figure 4 illustrates the use of joining technique in the battery packs. They include semi-automatic spot welding and automatic laser welding, which are used in the manufacture of lithium-ion batteries. In the semi-automatic spot-welding technique, electrodes are used to press and pass electrical current to join the tabs or nickel strips to the battery cell. Although this technique involves human interaction, it is widely used because of its simplicity and cost-effectiveness. Nevertheless, this technique produces more heat and is not too precise. On the other hand, the automatic laser technique involves the use of a precise laser beam to create precise and strong joints with minimal heat produced. This technique is precise, accurate, and faster, thus suitable for use in battery pack manufacture.

2.4. Battery Management System (BMS) Integration

The BMS acts as the intelligent control unit of the battery pack. During integration, voltage sensing wires are connected to each series cell group, allowing real-time voltage monitoring. Temperature sensors embedded in modules are interfaced with the BMS for thermal supervision. A current sensor (Hall-effect or shunt-based) is installed to measure pack current during charge and discharge. The BMS also includes protection circuits, balancing circuits (active or passive), communication interfaces (CAN, UART, or RS485) and safety relays [10]. After hardware integration, firmware configuration and calibration are performed. The BMS ensures protection against overvoltage, undervoltage, overcurrent, short-circuit, and thermal faults. Proper integration is essential to maintain operational safety, performance optimization and regulatory compliance.

Thermal management plays a critical role in lithium-ion battery safety and lifecycle performance. Research studies indicate that maintaining cell operating temperatures between 20°C and 40°C can improve battery life by nearly 25–30%. Active air-cooling systems provide economical thermal management for 2W applications, whereas liquid cooling systems are preferred in high-capacity 3W and commercial battery applications due to their superior heat dissipation capability.

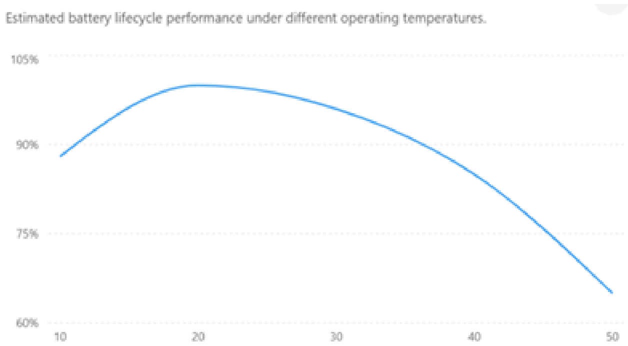

Figure 5: Effect of Operating Temperature on Battery Lifecycle

2.5. Module Testing and Pack Assembly

Before final pack integration, each module undergoes electrical and insulation testing. Voltage verification confirms correct series configuration. Insulation resistance testing ensures proper isolation between high-voltage components and the pack enclosure. Continuity tests validate electrical pathways, while functional tests verify BMS communication and balancing circuits [11].

Once modules pass validation, they are installed into the pack enclosure. At this stage, additional components such as cooling systems (air ducts or liquid cooling plates), high-voltage connectors, fuses, contactors, and protective relays are integrated. Mechanical fastening ensures structural rigidity. The enclosure is sealed to meet required Ingress Protection (IP) ratings for dust and moisture resistance. Proper routing of high-voltage cables and harnesses is crucial to prevent electromagnetic interference and mechanical wear [12].

Figure 6: Pack testing Machine

Figure 6 shows a battery pack testing machine HRDC-100V20A used in lithium-ion battery production. The machine is used to test the performance, safety and reliability of the assembled battery packs before they are shipped out or used for specific purposes. The machine carries out charge/discharge cycling, voltage/current measurement, capacity testing, and protection function testing, among other tests. The battery pack testing ensures that the battery meets the required standards, safety, and performance before it is used.

2.6. PDI (Pre-Delivery Inspection)

Pre-Delivery Inspection (PDI) is the final quality assurance stage before shipment or system integration. The battery pack undergoes comprehensive validation, including controlled charge, discharge cycling to verify capacity and efficiency [13]. Thermal monitoring ensures that temperature rise remains within specified limits. Leak tests confirm sealing integrity, especially in liquid-cooled designs. Mechanical inspections evaluate vibration resistance and structural integrity. Firmware validation ensures proper BMS communication and safety logic functionality. In automotive applications, high-voltage isolation and compliance with safety standards are verified. Any detected fault results in rework or rejection. Only after successfully passing PDI is the battery pack approved for dispatch or integration into electric vehicles or energy storage systems [14].

3. Automation and Mechatronics in Battery Manufacturing

Automation and mechatronics are playing a vital role in lithium-ion battery manufacturing. With an increase in demand for battery packs around the globe, manufacturers are shifting from traditional manual assembly to highly automated and intelligent systems. This helps in achieving high production efficiency with high precision and accuracy in product quality [15]. Gigafactories are huge lithium-ion battery manufacturing plants that require highly efficient automated assembly systems to produce millions of battery cells/packs annually.

Companies such as Tesla are using highly efficient automated battery manufacturing systems to improve manufacturing quality and consistency. The mechatronics system in lithium-ion battery manufacturing plants consists of sensors, actuators, robotic manipulators, programmable controllers, and data acquisition systems to control and monitor the entire production process [16].

Industrial studies indicate that automated battery manufacturing lines can reduce assembly defects by 35–50% compared to conventional semi-manual processes. Machine vision systems and automated welding technologies improve welding precision by up to 40%, while digital traceability systems reduce process downtime and quality-related rejections significantly. Advanced Manufacturing Execution Systems (MES) also improve production traceability and process repeatability in gigafactory environments.

3.1. Automated Production Lines

An automated manufacturing line consists of interconnected machines and robotic systems that carry out successive manufacturing operations with little or no human intervention. Production lines used in lithium-ion battery manufacturing include conveyor systems, robotic manipulators, precision positioning systems, and programmable logic controllers [6]. An automated manufacturing line in lithium-ion battery manufacturing can be used for the following operations:

- Handling and transportation of cells
- Stacking or winding electrodes
- Assembling modules
- Welding/electrical interconnections
- Quality inspection/testing

An automated manufacturing line can greatly improve production rates and lower manufacturing errors.

3.2. Machine Vision Systems for Quality Inspection

Machine vision technology plays an important role in the manufacturing of batteries. The vision system uses high-resolution camera technology and optical sensors to inspect the products during the manufacturing process [16]. The machine vision system is employed for:

- Cell surface defect detection

- Weld quality inspection
- Barcode recognition and traceability

High-speed vision technology enables the detection of defects in real time, reducing losses in the manufacturing process and improving the quality of the products [17].

3.3. Sensor Integration and Monitoring Systems

Contemporary battery production lines use sensor technologies extensively to sense the conditions of the process and maintain the stability of the process [16][17]. Some of the commonly used sensors in the process of battery production include:

- Temperature sensors
- Pressure release vent
- Position sensors
- Laser displacement sensors
- Optical sensors

Some examples of the application of the above-mentioned sensors include: Temperature sensors monitor the temperature of the welding process to prevent overheating. Position sensors monitor the alignment of the battery cells and Laser sensors monitor the depth of the weld.

3.4. Data Acquisition and Production Monitoring

Data acquisition systems are responsible for the collection and analysis of data from manufacturing equipment [4][16]. The key functions include:

- Production tracking
- Equipment performance tracking
- Detecting defects

Manufacturing Execution Systems (MES) are used by manufacturers to manage production data. The key data sources for a MES include:

- Assembly line data
- Testing log data
- Quality inspection data
- Warehouse data

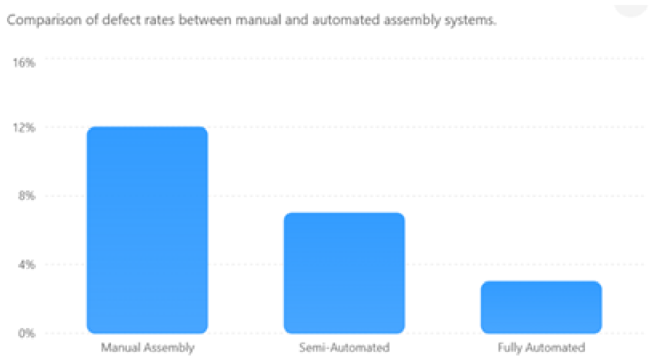

Figure 7: Manufacturing Defect Reduction Using Automation

4. Sustainable and Green Manufacturing Approaches in LIB Production

Sustainability has emerged as an important factor in battery manufacturing with the rise in environmental concerns, availability of resources and government policies. Lithium-ion battery production consumes a lot of raw materials such as lithium, cobalt, nickel, copper, and aluminum. Moreover, the process of battery manufacturing is also an energy-intensive process. With the rapid growth in demand for electric vehicles and other energy storage devices, it is important to reduce the environmental impact of battery manufacturing by incorporating sustainable manufacturing practices [18]. Sustainable manufacturing practices are mainly concerned with reducing the impact on the environment, maintaining high efficiency in the production process and ensuring high performance in the final products. Sustainable manufacturing practices in battery production would help optimize the consumption of resources, minimize waste generation and incorporate recycling and reuse in battery production. The International Energy Agency highlights that sustainable battery production is critical for facilitating the transition to low-carbon energy systems and clean transportation [19].

One of the most important sustainable practices involved in the production of batteries is the recycling of spent batteries. Lithium-ion batteries are comprised of valuable elements such as lithium, nickel, cobalt, copper, and aluminum. The selection of materials also plays a significant role in enhancing the sustainability of lithium-ion batteries [20]. Researchers of lithium-ion batteries have been focusing on the development of new cathode materials to reduce the dependency of these materials on rare and environmentally sensitive materials, i.e., cobalt. Researchers have been focusing on the use of alternative materials, i.e., Lithium Iron Phosphate (LFP), as they offer better safety and lifecycle benefits to the batteries and completely eliminate the use of cobalt [21]. Other sustainable material options for lithium-ion batteries:

- The use of recycled metals for the production of electrodes
- The use of cobalt-free cathode materials
- The reduction of toxic solvents used for the production of the electrodes
- The use of environmentally friendly electrolytes

5. Indian Standards, Safety Regulations and Certifications for LIB Packs

India has established a set of rules to ensure the safety, reliability and performance of lithium-ion battery packs for use in EVs and other energy storage systems. These rules are set by various regulatory bodies such as the Bureau of Indian Standards (BIS) and automotive regulatory bodies such as the Automotive Research Association of India (ARAI), National Automotive Test Track (NATRAX) under the supervision of the Ministry of Road Transport and Highways (MoRTH) [36]. The main standards set by India for lithium-ion battery packs are related to the design, electrical safety, thermal safety, testing, transportation, environmental protection and manufacturing quality. The key standards for lithium-ion battery use in EVs are AIS-156, AIS-038, AIS-048 and the BIS standard for lithium-ion batteries [22].

Figure 8: Indian Standard and national compliance

One of the most important safety standards that define the safety of EV batteries in India is AIS-156. AIS-156 is a standard that was developed to address the safety of the battery packs used in electric two-wheelers and three-wheelers. AIS-156 was developed after a spate of EV battery fires occurred in India. A new standard with stringent thermal management, battery monitoring, and safety validation tests was developed [21]. In addition, BIS certification ensures that battery cells and electronic components meet national quality and safety requirements through standards such as IS 16046, which aligns with international safety guidelines. The BIS certification process involves laboratory testing, manufacturing inspection, and compliance verification before granting approval to use the ISI quality mark [23]. Together, AIS and BIS certifications ensure that battery systems used in electric vehicles in India meet strict standards for safety, performance, and reliability before being introduced to the market.

6. Quality Assurance in Engineering Process

The Quality Assurance in the engineering process of the lithium-ion battery pack manufacturing process is defined as a set of standards that ensure the safety, reliability, consistency, and compliance of the product throughout its life cycle. Quality Assurance is more focused on preventive measures, standardized processes, and improvement, unlike the defect-control process. In the high-performance lithium-ion battery pack used in electric vehicles, energy storage systems, and industrial applications, Quality Assurance is present in every step of the engineering process [24].

The QA process starts with Incoming Quality Control (IQC), which checks and tests lithium-ion cells before they are put into service. Factors such as capacity, open-circuit voltage (OCV), internal resistance (IR), and physical integrity are checked using precision measurement devices. The lithium-ion cells are then graded and sorted to ensure that there is minimal variation within a module (0.2-0.5% deviation in capacity is acceptable). Statistical Process Control (SPC) is sometimes used for uniformity checks. Proper matching of lithium-ion cells will prevent imbalances, overheating, and capacity loss of the pack. In the assembly of the module, the QA process is centered on the mechanical structure's robustness and the low-resistance electrical connections. Laser welding conditions, such as pulse length, penetration, and consistency, are verified to guarantee the module's interconnections. A pull strength test, along with visual inspections, is used to identify weak weld joints in the module. The torque of the fastening equipment is calibrated to prevent loose connections and structural stress in the module. Electrical continuity and insulation resistance tests are conducted at intermediate stages to prevent short circuits and leakage paths [25].

The Battery Management System is a safety-critical system, and its integration process must be properly validated. QA activities involve firmware verification, sensor calibration for voltage and temperature, and functionality testing for the protection mechanisms such as over-voltage protection (OVP), under-voltage protection (UVP), over-current protection (OCP), and over-temperature protection (OTP). Communication protocols such as the CAN bus must also be verified for reliability [26]. In high-end laboratories, hardware-in-the-loop simulations can be used to simulate actual conditions to validate the BMS before the pack is sealed.

Before dispatch, End of Line testing of each battery pack is carried out. This involves capacity verification, internal resistance measurement, high voltage dielectric testing, short circuit detection, and comprehensive BMS testing. In some instances, aging tests are carried out to detect infant failure mode issues. A serial number is assigned to each battery pack.

This number corresponds to manufacturing and testing records, thereby offering full traceability. A structured approach to a Quality Management System (QMS), which is often based on the ISO 9001:2015 standard, is followed for documentation control, calibration records, inspection records, and audit trails. Standards such as those issued by BIS (IS 16046), IEC 62133, UN 38.3, and automotive safety regulations ensure that products are approved for marketing. Failure Mode Effect Analysis (FMEA), Root Cause Analysis (RCA), Six Sigma, Kaizen, etc., ensure that products are free from defects for long-term reliability [27].

7. CONCLUSION

The engineering process and system integration of lithium-ion cells into high-performance battery packs is a multidisciplinary activity that combines electrochemistry, mechanical design, power electronics, and safety compliance. While individual lithium-ion cells provide the fundamental energy storage capability, their transformation into a reliable, durable, and application-specific battery pack requires precise coordination of design, manufacturing, and validation processes. A well-engineered battery pack begins with rigorous cell selection, sorting, and grading to ensure uniformity in capacity, internal resistance, and voltage characteristics. This foundational step directly influences pack lifespan, safety margin, and overall performance consistency. Mechanical integration include module design, enclosure structure, vibration resistance, and IP protection ensures structural integrity under real-world operating conditions such as automotive loads, industrial use, or renewable energy storage systems. Electrical integration through optimized series-parallel configuration, low-resistance busbar design, and precision laser welding minimizes losses and enhances current handling capability. At the system level, the Battery Management System (BMS) serves as the intelligence core of the pack, performing real-time monitoring, protection, balancing, and communication with external controllers. Advanced BMS algorithms further improve safety, State of Charge (SOC) accuracy, State of Health (SOH) prediction, and lifecycle optimization.

Thermal management remains one of the most critical determinants of high-performance battery operation. Whether through passive air cooling or active liquid cooling systems, maintaining uniform temperature distribution prevents degradation, thermal runaway risks, and performance inconsistencies. Integrated safety systems — including fuses, contactors, current interrupt devices, and multi-layer protection strategies — ensure compliance with standards such as BIS, IEC 62133, UN 38.3, AIS-156, and NATRAX validation requirements in the Indian context.

From a systems engineering perspective, high-performance battery packs are no longer standalone components; they are intelligent energy platforms integrated with power electronics, fast-charging infrastructure, IoT monitoring systems, and smart energy management networks. This integration enables higher efficiency, predictive maintenance, and application-specific optimization for electric vehicles, three-wheelers, stationary storage, and industrial applications.

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