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Laser-based manufacturing for the electric powertrain

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A B S T R A C T

Laser-based manufacturing (LBM) is a key enabling technology for electric powertrain production, playing a fundamental role in both current and future manufacturing of batteries, fuel cells and electric drives. This keynote provides a review of applications of LBM across the manufacturing chain, linking process physics with system-level requirements and identifying performance, scalability limits and technology readiness across applications. Emphasis is placed on laser–material interaction, advanced optics, monitoring, data-driven control and simulation methodologies, including physics-driven and data-driven, as enablers of robust, high-volume production. The keynote also highlights the strategic role of LBM in enabling next-generation technologies, including solid-state batteries (SSBs).

1. Introduction

Battery electric vehicles (BEVs) are widely recognized as the most promising alternative to internal combustion engine (ICE) vehicles. However, their large-scale deployment and full replacement of ICE technology are still constrained by fundamental manufacturing challenges. Among these, limited driving range remains an important factor, but the most critical barrier is the higher production cost associated with BEVs.

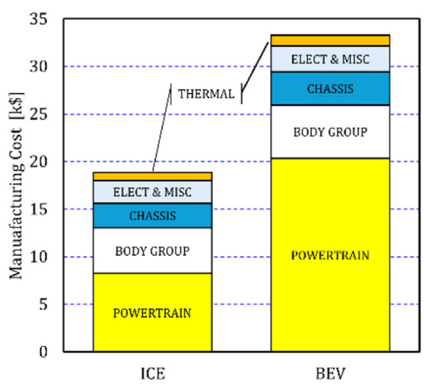

Fig. 1. Manufacturing cost analysis of ICE and BEW (data from [212]).

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As illustrated in Fig. 1, this cost gap is largely driven by the electric powertrain, which represents the most complex and expensive part of the vehicle. In particular, the battery pack, electric motor and power electronics account for the majority of the additional manufacturing cost compared to ICE vehicles. Reducing these costs while maintaining performance and reliability is therefore a key objective for enabling the widespread adoption of electric mobility [209].

In this contest, LBM, estimated to account for 60–80% [242] of material processing applications, plays a significant role in EV production. Key applications include laser cutting, surface treatments (e.g., ablation, structuring and drying), and welding. Recent advances in laser sources and scanning optics have enabled more efficient material utilization, higher processing speeds and improved product quality. These improvements are essential to support the expected growth of the EV market while reducing manufacturing costs. Furthermore, the integration of LBM with digital twins and intelligent control systems offers significant potential to reduce defects, optimize processes and minimize material waste. Fuel cell electric vehicles (FCEVs) remain less mature than battery EVs, but they represent a promising near-term alternative for specific applications, such as heavy-duty trucks and buses.

1.1. Energy storage systems: liquid-based electrolyte lithium-ion battery

The liquid-electrolyte lithium-ion battery (LIB) is currently the most widely adopted energy storage technology, outperforming alternative solutions in terms of cost, safety, energy density and power density [86]. For these reasons, LIBs are considered the

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reference technology throughout this paper. Liquid-electrolyte lithium-ion battery consists of a cathode, an anode, a separator, a liquid electrolyte and two current collectors (CCs). The negative electrode comprises a graphite active material supported by a copper current collector, while the positive electrode is usually formed by a layered $LiFePO_4$ (LFP) cathode on an aluminum current collector [59]. These material considerations are common to all major LIB cell formats used in automotive applications, including cylindrical, prismatic and pouch cells. Although specific steps vary with cell geometry, LIB manufacturing generally comprises three main phases [242]:

1. **Electrode production (EP)** includes mixing active materials for anodes and cathodes, coating CCs, continuous drying of the coatings, calendering, slitting the coated foils into smaller rolls, deburring and final vacuum drying.
2. **Cell production (CP)** involves cutting electrodes to the required geometry, stacking and electrically connecting them, inserting the assembly into the cell casing, electrolyte filling and final sealing.
3. **Assembly (A)** covers module and pack assembly, battery management system (BMS) integration and battery recycling.

To provide a concise manufacturing-oriented overview, Table 1 summarizes the main stages of the lithium-ion battery production cycle and highlights where laser-based processes are currently applied.

Table 1
Basic description of the LIB production cycle, from mixing preparation to pack assembly in a vehicle, including the laser processes applied in industry and/or under development for electrode production (EP), cell production (CP) and pack assembly (A).

Battery manufacturing process	Laser-based function	Purpose/benefit
Slurry drying (EP)	Laser drying (localized heating)	Reduced drying time, lower footprint, improved process control
Electrode structuring (CP)	Laser ablation/perforation	Tailored porosity, improved ion and electron transport
Electrode shaping (CP)	Laser cutting	High precision, design flexibility, tool-free processing
Current collector processing (CP)	Laser cutting/trimming	Clean edges, reduced burrs, high-speed processing
Surface preparation (CP)	Laser cleaning	Removal of oxides and contaminants, improved wettability
Interface engineering (CP)	Laser surface texturing/modification	Enhanced electrode–electrolyte contact, reduced interfacial resistance
Cell sealing (CP)	Laser welding	Hermetic sealing with minimal thermal impact
Cell cleaning (CP)	Laser ablation	Impurity removal before pack assembly, with minimal thermal impact
Cell assembly (Tabs, Busbars) (A)	Laser welding	High-speed, low-distortion joining, automation compatibility
Selective reworking (A)	Laser ablation/cutting	Local defect correction without full disassembly
Disassembly & recycling (A)	Laser cutting/delamination	Non-contact, selective material separation

1.2. Energy storage systems: fuel cells

Fuel cell electric vehicles (FCEVs) still lag behind BEVs in market adoption. This is mainly due to lower overall efficiency, the need for a battery pack to support regenerative braking and peak power demands and the high cost of fuel cell (FC) modules [142]. However, hydrogen and other fuels can potentially offer longer driving ranges without the use of heavy battery packs. Fuel cell technologies vary widely in electrolyte types, catalyst materials, operating temperatures and fuels, leading to different levels of technological maturity [4]. Among these, proton exchange membrane fuel cells (PEMFCs) operate at temperatures up to 120 °C. They use a thin polymer membrane in contact with the electrodes, separated by porous gas diffusion layers (GDLs) and catalyst layers (CLs), which together form the membrane electrode assembly (MEA). Commercial FCEVs typically employ stacks of PEMFCs fueled with pure hydrogen, enabling high energy density. The overall energy system includes a hydrogen tank, gas supply systems for H_2 and air, the fuel cell stack and a cooling system for thermal management. An auxiliary battery pack is required to handle bidirectional power peaks [179]. Bipolar plates (BPs) account for approximately 60–80% of the total mass of PEMFCs and provide mechanical support to the MEA while enabling gas distribution, water management, and heat dissipation [51]. Bipolar plates can be manufactured from graphite, which offers excellent thermal, electrical and chemical properties but suffers from brittleness and limited manufacturability. Alternatively, thin metallic plates made of stainless steel, titanium, nickel, or aluminum provide the mechanical strength required for FCEV applications. Due to the harsh, low-pH operating environment of PEMFCs, metallic BPs must be protected with suitable coatings, such as inert metals, nitrides, carbides, oxides, carbon-based layers, or conductive polymers. Both sides of the BP are engineered to optimize gas and fuel distribution at the cathode and anode. Thermal management is achieved through integrated cooling channels, typically obtained by sealing two preformed halves [179]. The production of metallic BPs begins with sheet forming processes such as stamping, hydroforming, rubber forming, or roll forming, followed by sealing the two halves via welding or adhesive bonding. Laser-based cutting and welding are the most widely used manufacturing techniques for BPs (see Fig. 2).

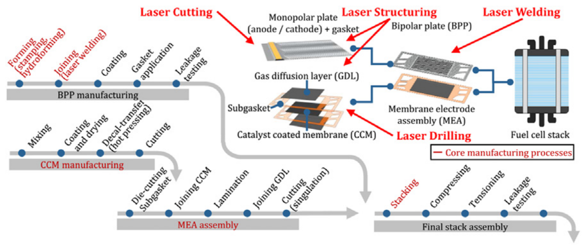

Fig. 2. Diagram of the process chain for PEM fuel cell production. Laser (adapted from [59]).

1.3. Electric drives

Traction systems in EVs are significantly simpler than those in ICE vehicles. Electric drives must deliver high starting torque to meet acceleration demands, achieve high power density to minimize size, and operate with high efficiency to maximize driving range. Currently, EVs mainly use AC induction motors and interior permanent magnet (IPM) motors [99]. Fig. 3a illustrates the main components of an EV traction system, which consists of a stator and a rotor. The stator consists of a hollow cylindrical steel core containing copper windings with large cross-sections to carry high currents. Winding configurations can be distributed or concentrated and may use stranded or hairpin conductors. Hairpin windings offer higher slot fill factors, increased power density, improved overload capability and enhanced thermal performance [107]. The rotor contains the magnetic elements of the motor, which can be either permanent magnets or inductive components generating a magnetic field through asynchronous operation. Rectangular conductors are first formed into individual segments [190], while electrical steel laminations are stacked and insulated. The conductors are then inserted into the stator slots, forming hairpin ends that are subsequently joined and insulated by resin impregnation. As shown in Fig. 3b, LBM is mainly employed for surface preparation and electrical connections, including hairpin stripping and laser welding. Additionally, laser welding is used to join the stacked steel laminations [36]. These processes are critical, as defective joints can lead to performance degradation of the electric drive over time.

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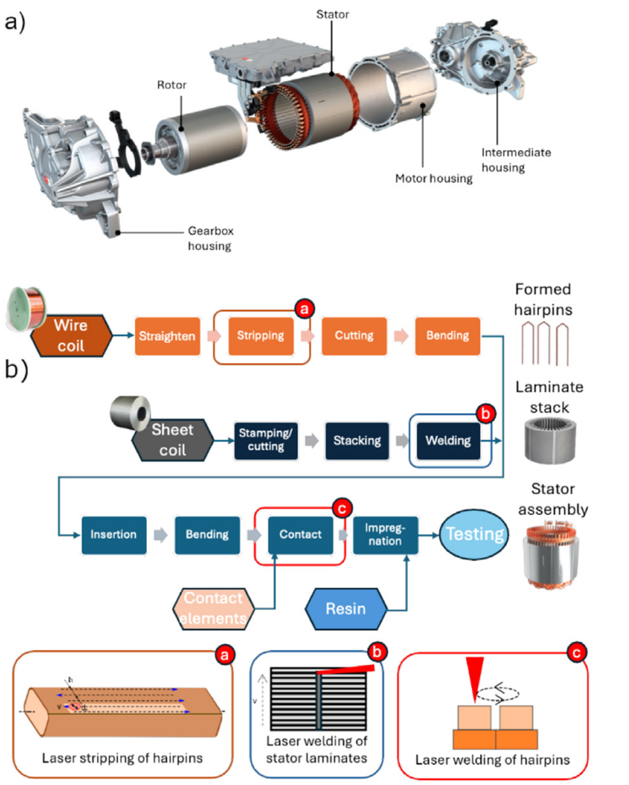

Fig. 3. a) Components of an electric drive (Adapted from Volkswagen Group [216]). b) The production stages of an electric drive based on hairpin technology highlighting the laser-based manufacturing processes involved.

1.4. Scope of the paper

Although laser-based manufacturing for electric mobility has been widely investigated, most studies adopt a fragmented perspective. They are typically product-, process-, or application-specific, focusing on individual components [229], or they address manufacturing at a broader system level without detailed process integration [154]. As a result, a comprehensive approach that integrates product requirements, manufacturing processes and system design is still lacking. This gap is particularly evident at the powertrain level, where no study provides a unified analysis across all key components. This review addresses this gap by presenting a manufacturing-oriented analysis of LBM for batteries, fuel cells and electric drives. It explicitly links process physics with system-level aspects such as monitoring, control and simulation. By adopting a process- and system-centric perspective, the paper identifies key manufacturing bottlenecks, assesses technology readiness and outlines directions for scalable and intelligent industrial deployment, while excluding electrochemical material design and vehicle-level integration.

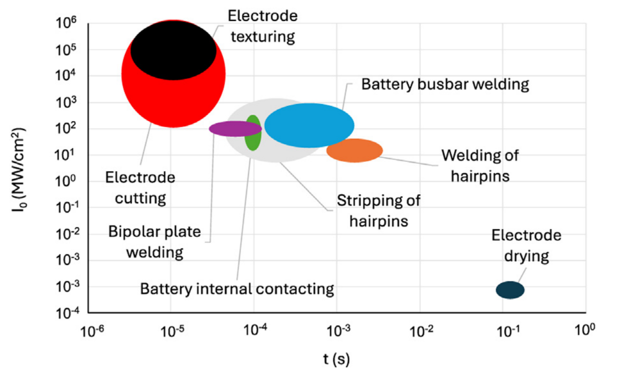

Fig. 4. Peak irradiance and interaction time for the main LBM processes for the electric mobility applications (adapted from Steen and Mazumder [199] and rearranged with the literature data).

2. Landscape of industrial laser systems

2.1. Laser sources and interaction regimes in EV-manufacturing

The availability of industrial laser equipment is analyzed to highlight the wide range of system configurations and options. Laser system components are selected and assigned to specific processes based on their primary requirements, particularly in terms of the desired laser–material interaction (e.g., heating, fusion, or ablation). Laser–material interaction can be described using two key parameters: (i) peak irradiance and (ii) interaction time. Peak irradiance is defined as the ratio between laser power and spot area. Interaction time is defined as the ratio of spot diameter to beam velocity for continuous wave (CW) lasers, or as the pulse duration for pulsed wave (PW) lasers [196]. Fig. 4 illustrates the distribution of LBM processes in electric mobility, based on typical ranges of peak irradiance and interaction time. Electrode drying requires the longest interaction times, as it uses wide beams with low peak irradiance levels. Welding processes also involve relatively long interaction times, combined with high peak irradiance, especially for thicker components in batteries and electric drives. As component thickness decreases, interaction time is reduced and peak irradiance increases. Hairpin stripping typically employs PW lasers operating in the µs to ns range. Remote cutting and surface texturing require high scanning speeds and small beam diameters, resulting in short interaction times. For electrode cutting, both CW and PW lasers are used, covering a broad range of irradiance conditions. In contrast, surface texturing relies on highly intense beams combined with high scan speeds. The typical allocation of laser sources for electric drivetrain manufacturing is summarized in Table 2 covering heating, fusion and ablation-based processes. The following sections provide a detailed analysis of the laser source types available for different processes. They are organized according to the intended laser–material interaction, namely heating, fusion and ablation, highlighting their main characteristics,

Table 2
Laser source allocation for heating, melting, and ablation-based processes used in electric powertrain manufacturing.

Characteristics	UV	Blue	Green		NIR	IR
Wavelength	350–355 nm	440–450 nm	530–535 nm	800–950 nm	1030–1080 nm	9300–10,600 nm
Laser source	Frequency tripled Nd:YAG or fiber	Diode	Frequency doubled Nd:YAG or fiber	Diode	Fiber; Disc	CO_2
Power range	Up to100 W	Up to 6000 W	Up to 3000 W	Up to 100 kW	Up to 200 kW	Up to 1 kW
Typical beam size	5–20 µm	700–1000 µm	30–400 µm	>1000 µm	50–500 µm	100–1000 µm
Main application - CW	n/a	Welding in electric drive and battery systems	Welding in electric drive and battery systems	Electrode drying	Welding in electric drive and battery systems. Electrode cutting.	
Main application -PW	Hairpin stripping with ns pulses	n/a	Hairpin stripping with ns pulses	n/a	Electrode cutting and texturing. Hairpin stripping.	Hairpin stripping

with a focus on industrial solutions. Data was sourced online from the producers' websites (AMPHOS, Bright Solutions, Changchun, Coherent, Dausinger+Giesen, INNOLAS, IPG, Light Conversion, Jenoptik, JPT, Lumentum, Luxinar, nLIGHT, Nuphoton, Raycus, Spectra Physics, Trumpf) and analyzed separately for different wavelengths and pulse durations.

2.1.1. *Lasers for heating and fusion-based processes*

Continuous-wave lasers for heating and fusion applications rely on near-infrared (NIR) fiber and disc laser sources. These technologies represent the most industrially mature solutions for processing key materials and are commercially available with power levels exceeding 100 kW. In e-mobility applications, NIR lasers are often equipped with core/ring beam shaping configurations, which are particularly suitable for welding (see (see Fig. 5a). Typical commercial setups are shown in Fig. 5b The analysis considers manufacturers providing detailed specifications, including total power, fiber dimensions and number of cores. Available power ranges from approximately 0.6 kW for quasi-continuous wave (QCW) lasers, with most systems operating between 4 and 10 kW and some reaching up to 24 kW. The beam irradiance profile depends on the core diameter and the number of surrounding rings. Both double- and triple-fiber configurations are available. Recent systems offer core diameters ranging from single-mode (12–25 µm) to multi-mode (50–100 µm). The ring diameter is typically scaled relative to the core, usually 3–4 times larger and can reach up to 10 times in some designs. These laser sources are commonly integrated with high-aperture scanner heads (20–30 mm), including collimation and focusing optics with magnification factors between 1.5 and 5 [103]. The available sources also differ in terms of the power control across the core and the ring. Two types of strategies exist in this case: (i) the ring and the core are independently powered by two separate sources [200]; (ii) they share a single source that distributes part of the total power to the core and part to the ring [66]. Separate laser sources enable flexible control of power distribution between the core and the ring. However, maximum output is achieved only when both operate at full power. In power-sharing configurations, a single source distributes power between the core and the ring. This allows full utilization of the available power but offers less precise temporal control of the beam profile. The main advantage is a more cost-effective solution for a given total power. Based on beam quality and fiber diameter, core/ring laser systems can be classified into three main categories. Pure single-mode (SM) systems emit single-mode beams from both the core and the ring. Mixed-mode systems combine a single-mode core with a multi-mode ring. Pure multi-mode (MM) systems emit multi-mode beams from both regions (Table 3). The commercial availability of high-power lasers at visible wavelengths have significantly increased in the last half decade. Copper, aluminum and their alloys as well as steel grades all benefit from higher optical absorption of green and blue lasers especially for welding applications [109]. The green laser wavelength (515–535 nm) can be produced via frequency doubling of a source with NIR radiation (1030–1070 nm).

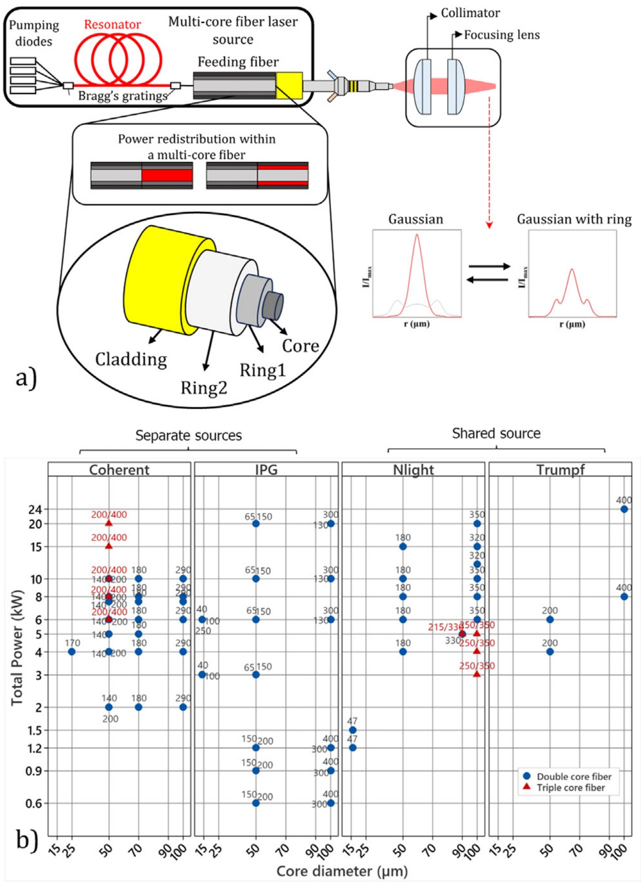

Fig. 5. a) Schematic description of a fiber laser source with multiple core delivery fiber used for core/ring beams. b) Distribution of the industrial fiber and disc laser sources operating at NIR wavelength with core/ring beam configuration as a function of fiber core diameter and total power. The data labels depict the ring size, where two values refer to the first and second ring diameter in µm. The laser sources are divided as a function of producers that provide control of separate sources in the ring and the core as well as a single source shared between the ring and core. All data were acquired by 26 May 2025.

Table 3
A general classification of ring/core laser sources according to the beam quality and fiber diameters. All data were acquired by 26 May 2025.

Type	BPP core [mm·mrad]	BPP ring [mm·mrad]	Ø core fiber [µm]	Ø ring fiber [µm]
Pure SM	0.4–0.5	1.6–1.8	14–16	40–45
Mixed mode	0.4–0.8	3.5–15	14–20	100–300
Pure MM	2.0–4.0	3.5–20	50–100	100–400

Fig. 6 shows the distribution of the different green laser sources as a function of the power, beam parameter product (BPP) and emission mode. The analysis was limited to the producers providing the detailed description of the power, beam parameter product, source architecture and emission mode. Laser sources with power levels less than 5 W were not considered. The diode laser sources currently operate at low power levels up to 100 W with relatively high beam quality. At higher power levels, CW operation becomes problematic because of rapid thermal wear in harmonic-generating crystals. A possible solution is to use PW emission with high repetition rates in the MHz range and low pulse energies, which results in low peak power but maintains a relatively high average power of a few hundred watts [192].

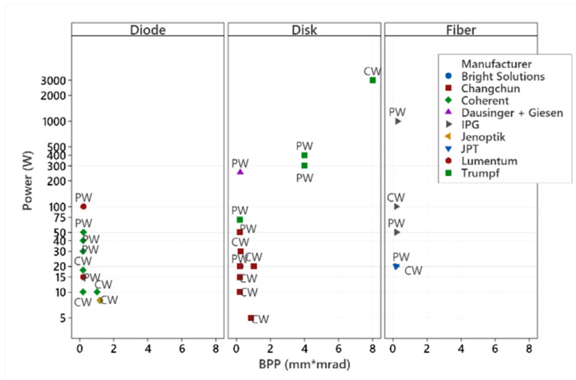

Fig. 6. Distribution of the industrial fiber, disc and diode laser sources operating at green wavelength as a function of beam parameter product (BPP) and power along with the emission mode. Data acquired by 26 May 2025.

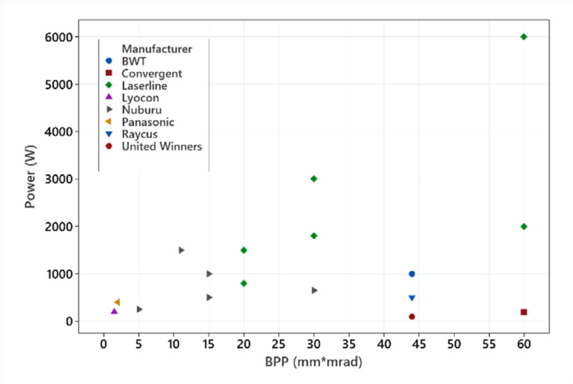

Fig. 7. Distribution of the industrial diode laser sources operating at blue wavelength as a function of beam parameter product (BPP) and power. All data were acquired by 26 May 2025.

The need to process highly reflective materials, such as copper, has driven the development of direct diode blue lasers (440–450 nm). Fig. 7 depicts the industrial availability of blue diode lasers. The analysis is limited to manufacturers providing detailed specifications, including power and beam parameter product. Blue laser emission is achieved through direct electrical conversion in diode systems, resulting in high electrical efficiency. High-power blue diode lasers are currently under active development, with ongoing efforts focused on increasing output power while maintaining high beam quality [162]. Beam quality, in fact, is closely related to the power scaling strategy adopted in the design of the laser source. When diode lasers are scaled to high power levels in the NIR range (800–950 nm) using stacking and beam-combining strategies, they typically exhibit large beam sizes. In this configuration, they are widely used in heat treatment applications, such as slurry drying in electrode fabrication [152].

2.1.2. Lasers for ablation-based processes and remote cutting

Surface processing, cutting and remote cutting require laser sources with small beam sizes (10–50 µm) and high peak power. Pulsed-wave lasers are well suited for surface texturing, micromachining and ablation-based remote cutting. High-power single-mode (SM) and multimode (MM) fibre lasers are also suitable for remote cutting in electric mobility applications. Fig. 8 summarizes the availability of industrial laser sources for ablation processes and remote cutting. The analysis focuses on manufacturers of PW lasers and single-mode CW lasers that provide detailed specifications, including average power, pulse duration, and repetition rate. As shown in Fig. 8a, single-mode lasers are typically available at moderate power levels around 1 kW, although newer solutions can reach up to 10 kW. For multi-mode lasers, sources with fiber diameters up to 50 µm are suitable for remote cutting applications, where power levels can be scaled beyond 10 kW. Pulsed (PW) lasers, ranging from nanosecond (ns) to femtosecond (fs) regimes, are commonly available with average powers between 20 and 1000 W (see Fig. 8b). Nanosecond systems offer lower processing quality but benefit from compact size and reduced cost [43]. Processing quality improves when moving toward picosecond (ps) and femtosecond (fs) regimes, although these systems typically have a larger footprint. Due to the high peak power of ps and fs pulses, fibre-based delivery methods are still under development [130]. Recently developed fs-pulsed systems are available with average power levels above 2 kW. Along with average power, the pulse repetition rate (PRR) is a key parameter of PW lasers because it directly affects process speed. Ultrafast laser amplifiers can operate at several MHz. The same average power can be distributed either as high repetition rates with low pulse energy or as low repetition rates with high pulse energy. The correct combination for the given material can improve the machining efficiency [84]. The use of burst mode in the ps and fs pulsed laser sources provide added flexibility in the material processing applications for electric mobility

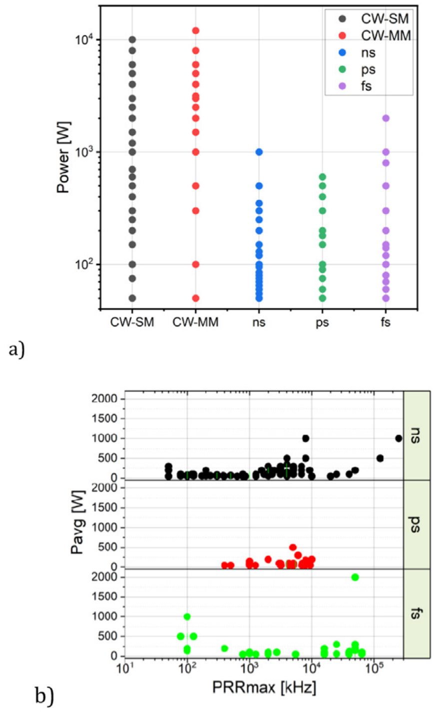

Fig. 8. Industrially available laser sources for remote cutting and ablation-based processes. a) Laser power distribution as a function of laser emission mode and pulse duration. b) Average power available to ns, ps, and fs pulsed lasers as a function of the maximum pulse repetition rate. All data were acquired by 26 May 2025.

[161], as will be discussed in Sections 3.1.2 (Laser structuring, perforation and ablation) and 3.1.3 (Laser cutting).

2.2. Beam steering systems and processing heads

Scanning systems and proximity heads are used in welding, cutting and ablation processes across electric drivetrain components. Their industrial availability is rapidly increasing to match advances in laser source technology, including higher power levels and new wavelengths. The data used in this analysis were sourced from manufacturers' websites. Scanning optics are widely used in electric mobility applications that require fast beam motion. Most systems are based on 2D scanner heads with f-theta lenses. These setups are adaptable for welding, cutting, and ablation. In contrast, 3D scanning systems are less common. They allow control of the beam along the propagation axis and enable focal position correction for height variations. Multi-axis and pre-focusing systems further improve flexibility in beam steering. Polygon scanners are used for very high scan speeds (>100 m/s), mainly in surface texturing applications [143]. Scanner systems are available across conventional IR, NIR, visible and UV wavelengths. In contrast, systems compatible with emerging blue lasers are still limited. The design of scanner systems is primarily determined by scan speed and maximum power handling. A key parameter linking these aspects is the input aperture. For welding applications, the maximum power capacity of the scanner is the critical factor, while scan speeds are typically low (<1 m/s). In contrast, for cutting and texturing processes, scan speed becomes more important, as the required power levels are generally lower (around 1 kW). Proximity heads are typically used in applications with relatively low processing speeds, particularly when the use of shielding gas or filler wire is required. The beam motion is provided by external manipulators such as cartesian axes or robotic systems. Industrial proximity laser welding heads can integrate several features, including filler wire nozzles, shielding gas nozzles (coaxial or off-axis), beam oscillation optics and seam tracking systems (lateral and vertical) using tactile or optical methods. Heads with filler wire typically support wire diameters of 1–2 mm. Systems with beam oscillation offer highly dynamic performance, with frequencies up to 900 Hz and amplitudes up to 10 mm. In electric drivetrain applications, laser welding often

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requires shielding gas or filler material, especially for large components such as battery cooling plates and body-in-white parts [123]. These processes are typically characterized by low welding speeds (<100 mm/s). The use of filler wire is beneficial for gap bridging and for improving weldability of crack-sensitive alloys [230]. Beam oscillation enables the formation of wider seams without increasing the beam diameter, enhancing gap tolerance, reducing porosity and promoting better mixing in dissimilar material welding [136]. Seam tracking is often required, as the proximity head must compensate for part-to-part variations through trajectory corrections [21]. Although proximity heads can also be used for cutting applications, their use in electric drivetrain manufacturing remains limited. The use of process gas to remove molten or ablated material during laser cutting of electrodes and stator laminations has been proposed, but industrial adoption is still scarce [224]. Fig. 9 presents the distribution of industrial proximity welding heads for NIR lasers (fiber and disc). The analysis is based on data from manufacturers providing detailed specifications on power handling and optical configurations. Systems with transmissive optics can handle up to 100 kW, with magnification factors up to 10. When beam oscillation is employed, additional optical components such as galvanometric mirrors or rotating prisms are required, reducing the maximum handled power to approximately 30 kW.

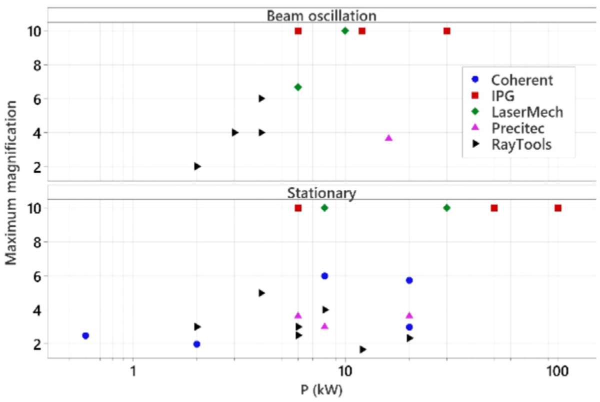

Fig. 9. Industrially available proximity heads for welding as a function of the maximum power handled and the maximum magnification available in the optical configurations. Processing heads with stationary beams and beam oscillation are shown in separate panels. All data were acquired by 26 May 2025.

2.3. New optics and beam shaping

Laser−material interaction involves complex thermo-mechanical and fluid-dynamic phenomena. The intensity distribution, or beam shape, strongly affects thermal cycles and local temperature fields, and ultimately determines the material microstructure. Researchers have explored beam shaping technologies in heating and melting processes to control cooling rate, peak temperature and solidification rate, without changing the chemical composition of the substrate or workpiece [199]. Fig. 10 shows the EBSD (Electron Backscatter Diffraction) maps of two welds generated using shaped and unshaped beams. The results show that a shaped trailing beam, with extended melting at the rear, promotes the nucleation of equiaxed grains and refines the columnar structure on both sides of the fusion zone, thereby reducing cracking susceptibility. This effect is attributed to a lower melt flow velocity, improved stability of the molten pool, higher solidification rates and reduced thermal gradients compared to an unshaped Gaussian beam. While a tightly focused Gaussian beam provides the highest intensity over a small area, it is not always optimal. Beam shaping can be used to preheat the material before melting or vaporization, or to control the cooling rate at the rear and sides of the processing zone. This approach has led to three main categories of beam shaping for material processing: static, quasi-static and dynamic [101].

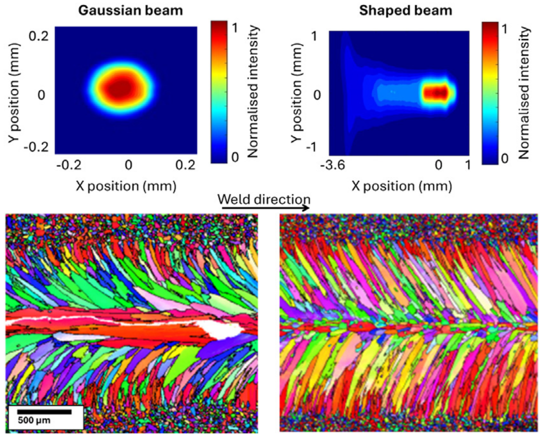

Fig. 10. Impact of static beam shaping on grain refinement applied to 6082 aluminum welding. The shaped beam has been generated with a freeform micro-lens from the unshaped Gaussian beam [167].

With the *static beam shaping*, diffractive, refractive or reflective optical elements are inserted in the optical chain and the incoming laser light is shaped to core-ring profile, square or non-axial-symmetric shapes. The conventional and most cost-effective way of beam shaping is by defocusing the laser beam to change the spot size. This approach was tested in [9] and demonstrated the impact on microstructure thereby controlling the solidification behavior and mushy zone size during welding. Recent studies have explored multi-spot welding, using diffractive beam splitters/shapers, to split a single input beam and create diverse beam shapes—e.g., ring, line, and row of spots. The work in [220] used a multi-spot design with two beams placed along the welding direction and found that it helped to increase the penetration depth. The research in [214] demonstrated improved keyhole stability using a 2 × 2 multi-spot grid. The implementation of a ring beam shape using a diffractive beam shaper led to a reduced thermal gradient along the fusion zone but with an increased amount of spatter and diminished mechanical properties. A significant body of literature has shown the benefits of axisymmetric laser beam shaping to reduced spatters [220], improved keyhole stability [219] and increased welding speed [44]. However, its impact on microstructure morphology remains poorly understood. A generalized form of core/ring technology is the Bessel beam, part of the broader class of non-diffractive optics. These beams maintain their shape over long working distances, resulting in an extended depth of focus. Bessel beams can stabilize molten pool flow and prolong solidification time, which affects grain structure in laser-based additive manufacturing. Other beam shapes, such as square profiles, have also been used to widen and elongate the molten pool while reducing thermal gradients, which are directly related to thermal stresses [184]. Using an elliptical Gaussian beam shape [55], with an aspect ratio of 1.4 can reduce the ratio of the thermal gradient to cooling rate, leading to refined microstructure. Furthermore, [55] shows that replacing a circular beam with annular, triangular, or square profiles increases the nucleation of equiaxed grains by 6.4%, 7.0%, and 6.0%, respectively. These results are based on modelling of thermal gradients and solidification rates. The problem with the static solutions is that they can only achieve a spatial modulation of the intensity distribution, not capable to enable multiple thermal cycles during the rapid solidification. Notably, for a laser welding in keyhole regime, any changes in the keyhole morphology and molten pool dynamics will manifest on a *microseconds* time-scale. Parallel to that, the solidification process occurs on a timescale of few milliseconds [186]. As a result, when attempting to solve well-known problems, i.e., solidification cracking and weld porosity, the laser must be applied not only with the correct spatial distribution, but also at the correct timescale. To address issues such as solidification cracking and weld porosity, the laser must be controlled not only in space but also in time. Dynamic beam shaping (DBS) has therefore become a key research focus. Galvo scanners are widely used to oscillate single-mode or

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multi-mode beams in complex Lissajous patterns (also called equivalent beam shapes) at frequencies up to tens of kHz. Extensive experimental studies show that this approach improves weld morphology and promotes equiaxed grain formation in the fusion zone through enhanced melt pool stirring [26]. Nonetheless, due to the scanning nature of this approach, undesirable cooling effects of the material will appear between the consecutive passes of the laser beam [218]. Non-scanned DBS approaches are the use of multi-plane light conversion, deformable mirrors [170] or optical phased array (OPA) with coherent beam combined (CBC) lasers [170]. In particular, the CBC—OPA technology has resonated with the scientific community since it allows creating, theoretically, endless number of beam shapes and sequences in the timescale of few hundreds of *nanoseconds*. CBC—OPA technology enables the generation of virtually arbitrary beam shapes on sub-microsecond timescales. Despite its potential, it is still at an early stage of development, with limited experimental validation. A key challenge remains the lack of fundamental understanding of material response to such rapid spatial and temporal thermal modulation, as well as the complexity associated with the large number of possible beam configurations. This will necessitate developing systematic modelling and optimization methodologies to contain the vast number of possibilities. Seamless integration of advanced macro-scale models (e.g., Marangoni forces, recoil pressure, buoyancy, and fluid-flow pressure) with micro-scale models (e.g., solute segregation at grain boundaries) is needed. This approach can be combined with advanced characterization techniques, such as high-speed X-ray imaging, to efficiently explore the large design space of dynamic beam shaping (DBS) [61]. It is worth noting that fast modulation in time and space can enhance grain refinement, but it may also introduce defects such as porosity due to instabilities in the molten pool and keyhole walls. Process optimization must therefore balance productivity, quality and sustainability.

2.4. Summary of laser systems, beam delivery and optics for electric mobility manufacturing

The previous sections highlight the wide range of laser technologies currently available for electric powertrain manufacturing. These solutions differ in terms of wavelength, emission mode, beam quality and system architecture, offering distinct capabilities depending on the required laser−material interaction. The following summary provides a structured overview to guide the reader and introduce their application in Section 3.

Laser sources for heating and fusion processes

- CW NIR fiber and disc lasers represent the most industrially mature solutions, offering high power (>100 kW) and robustness for welding and thermal processes.
- Core/ring beam configurations enable control of heat input distribution and are widely used in welding applications.
- Visible lasers (green, blue) improve absorption in highly reflective materials, enabling more stable processing.
- Diode lasers, especially when scaled through stacking and beam combining, are well suited for large-area heating processes such as electrode drying.

Laser sources for ablation and high-precision processing

- PW lasers (ns−fs) cover a broad range of applications from cost-effective processing (ns) to high-quality micromachining (ps, fs).
- Ultrashort-pulse lasers (ps, fs) enable minimal thermal damage and high precision, but are limited by cost, footprint, and throughput.
- Burst-mode operation and high repetition rates provide additional flexibility and efficiency, particularly for structuring and cutting processes.

Beam steering systems and processing heads

- Scanner-based systems enable high-speed beam positioning for cutting, welding and texturing.
- Proximity heads are used for lower-speed processes requiring shielding gas, filler wire, or seam tracking.
- System design depends on power and scan speed, with the aperture of scanner as a key linking parameter.
- Integration of monitoring and adaptive control is increasingly required for industrial robustness.

Beam shaping and advanced optics

- Static beam shaping (core/ring, diffractive optics) enables control of spatial energy distribution.
- Dynamic beam shaping (DBS) introduces temporal modulation, improving melt pool dynamics and microstructure control.
- Advanced approaches (e.g., CBC, deformable optics) offer high flexibility but are still at early development stages.
- Beam shaping introduces a large design space, requiring modelling, optimization and diagnostics.

Overall, the combination of laser sources, beam delivery systems, and advanced optics provides a highly versatile toolbox for electric mobility manufacturing. However, this flexibility also increases system complexity and the need for structured process design. In the following section, these technologies are analyzed in the context of their application to key components (batteries, fuel cells, and electric drives) highlighting how specific laser solutions are selected and adapted to meet process and system-level requirements.

3. Overview of laser-based manufacturing processes in electric vehicle components manufacturing

This section reviews the main LBM processes currently applied to the manufacturing of batteries, fuel cells and electric drives. The discussion begins with **battery production**, covering electrode drying, structuring and perforation, cutting of current collectors and electrodes, cell cleaning and laser welding at cell, module, pack and battery-case level. It then addresses **fuel cell** manufacturing, with particular focus on laser cutting, welding and structuring of bipolar plates. Finally, the section examines **electric drive** production, including laser stripping and welding of hairpins. For each application, the relevant components, process objectives, laser source configurations and main quality and performance aspects are analyzed, providing a process-oriented overview of the current state of the art.

3.1. Energy storage systems: manufacturing of batteries

The following sections present, in sequence, the main LBM processes applied to battery manufacturing, including electrode drying (Section 3.1.1), structuring and perforation (Section 3.1.2), cutting of electrodes and current collectors (Section 3.1.3), cleaning (Section 3.1.4), and welding at cell, module, and pack levels (Section 3.1.5). For each process, the associated components, laser systems, and key performance and quality aspects are discussed in detail.

3.1.1. Laser drying of electrodes

Standard LIB electrodes are produced by coating a slurry of active materials, conductive additives and polymeric binders onto metallic current collectors, followed by drying and calendaring [298]. Drying governs porosity and coating uniformity [83], which are critical for electrochemical performance, yet it remains a major source of defects [94]. Industrial web speeds of 25−80 m/min [135] require tightly controlled convection drying to avoid binder migration, motivating the use of combined drying strategies to increase throughput while preserving quality [105]. Compared to conventional convection furnaces, advanced laser drying modules offer significant potential to reduce plant footprint as well as capital and operating costs, provided that drying intensity is carefully controlled to prevent defect formation [147]. Owing to their high energy density, laser-based drying techniques therefore represent a promising approach to simultaneously lower manufacturing costs and enhance cell performance,

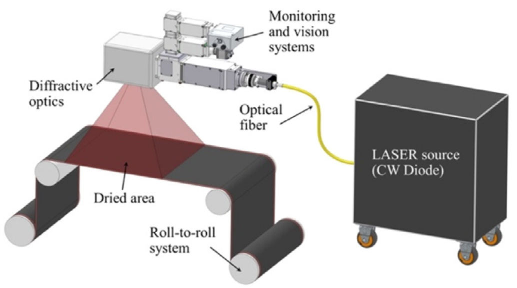

Fig. 11. Schematic of a laser-based electrode drying system in a roll-to-roll configuration.

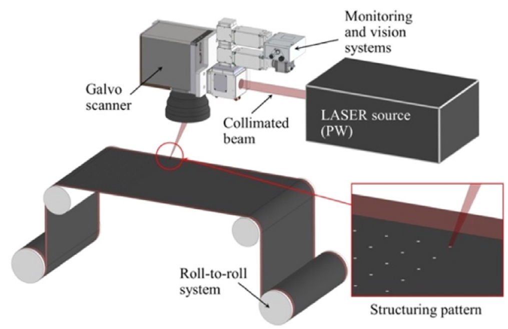

Fig. 12. Schematic of a laser-based electrode structuring process in a roll-to-roll system with the resulting micro-structured pattern (holes) on the moving electrode surface.

with studies indicating that near-infrared wavelengths are particularly well suited to achieve the temperature ranges required for electrode drying [153]. Fig. 11 illustrates the schematic layout of a laser-based electrode drying process in a roll-to-roll configuration.

Recent studies have demonstrated significant progress in laser-based electrode drying toward industrial relevance. In [211] controlled drying of both anodes and cathodes was achieved at laboratory scale using a 450 W diode laser. Electrode temperatures were maintained below 240 °C. A productivity of approximately 50 cm^2s^{-1} was obtained. In addition, energy consumption was reduced by about 50% compared to conventional oven drying. Subsequent investigations have explored the drying limits of laser processing for water-based anode slurries, showing that laser absorption is dominated by graphite and conductive carbon additives [57]. Excessively high drying rates can induce binder migration and reduce adhesion to the current collector. This may degrade electrochemical performance and promote delamination [102]. At the same time, these studies demonstrate the high-throughput potential of laser drying. Using a 6-kW diode laser with a homogenized 100 × 100 mm^2 processing area, evaporation rates up to 318 $g{\cdot}m^{-2}s^{-1}$ were achieved. This corresponds to more than an order-of-magnitude increase compared to conventional drying (≈15 $g{\cdot}m^{-2}s^{-1}$) [57]. More recent work has moved beyond stand-alone laser processes toward hybrid laser convection drying systems. An 8-kW diode laser with a top-hat intensity profile was integrated with a 2.1 m two-zone convection dryer. This configuration enabled laser-assisted drying during the early stages of film shrinkage. Under these conditions, electrode adhesion, electronic conductivity, and rate capability remained comparable to conventional convection drying. At the same time, overall drying time was reduced by up to 63%. These results demonstrate a clear pathway toward scalable and high-throughput laser-assisted drying solutions. To summarize, laser-assisted drying has progressed from proof-of-concept to a manufacturing-relevant technology, demonstrating order-of-magnitude gains in drying rate and significant energy savings. The main remaining challenge is balancing high throughput with microstructural integrity, positioning hybrid laser–convection systems as the most promising pathway toward scalable industrial implementation.

3.1.2. Laser structuring, perforation and ablation

Increasing electrode thickness or compression is an effective way to increase the active material fraction and therefore energy density and driving range. However, at high current densities, this approach limits ion transport through the porous electrode. As a result, practical limits on coating thickness are imposed [68]. To overcome this trade-off, several laser-based processes have been developed. **Laser structuring** (whose system configuration is schematically illustrated in Fig. 12) introduces microscopic channels or patterns within the electrode coating. These features typically extend up to about 80% of the coating thickness, without affecting the underlying current collector. This modification reduces internal overpotentials and shortens the effective diffusion paths of lithium ions, resulting in improved power density [77]. Early studies on cathode structuring demonstrated enhanced high-rate performance, as the presence of microchannels (holes) facilitates faster ion transport during charge and discharge [172].

A recent study focused on nickel–manganese–cobalt oxide ($LiNi_xMn_yCo\_zO_2$) (NMC) cathodes [206], reporting consistently improvements in lifetime, electrochemical performance and energy density. The benefits strongly depend on coating thickness and active material particle size, highlighting the importance of process–material interaction in laser structuring [195]. Laser structuring has also been extensively applied to graphite anodes, where it enables increased capacity [76], improved fast-charging capability and safer fast charging of high-energy-density cells [29]. In thick electrodes, structuring reduces side reactions while improving rate capability and volumetric capacity [166]. Studies using nanosecond (ns) pulsed lasers to create diffusion holes in graphite anodes and NMC cathodes showed that diffusion limitations can be reduced, especially in graphite [92]. Further studies analyzed how laser structuring affects the mechanical properties of graphite anodes. Changes in stiffness and adhesion were observed, mainly due to modifications in the electrode microstructure caused by the laser [91]. In addition, ps-laser structuring at wavelengths of 532 and 355 nm was shown to significantly improve electrochemical performance [89]. Automated, image-based methods have also been developed to quantify laser-induced structures and improve process reproducibility [87]. Unlike structuring, **laser perforation** creates through-holes across the full electrode thickness. These holes provide direct pathways for ion transport. Using ps-lasers, complete perforations have been achieved [207], leading to improved capacity retention at high discharge rates [208]. Laser perforation has also been shown to enhance rate capability, cycle life and power density in both LFP and NMC electrodes [225]. This indicates that perforation is particularly effective when diffusion limitations are severe. From a manufacturing perspective, ultrashort-pulsed lasers (ps [113] and fs [76]) are especially suitable for structuring and perforation. They enable precise material removal with minimal thermal damage, even when partially or fully penetrating the current collector. Process studies also showed that ablation depth increases with peak power and is influenced by plasma plume dynamics, particularly at high repetition rates up to 50 MHz [146]. Despite these advantages, industrial adoption remains limited. The main barriers are the wide range of electrode chemistries, limited understanding of long-term laser–material interactions [210], low production rates compared to industrial needs [88] and insufficient economic analysis. Only a few studies have addressed process-chain integration. One study showed that performing laser structuring after drying is the most effective approach within the manufacturing sequence [90]. Finally, laser surface texturing of current collectors (CCs) is a complementary process. Texturing of aluminum and copper collectors improves adhesion between the active material and the substrate [182]. It also enhances cyclability in LFP and NMC cathodes, as well as in graphite anodes [176]. This highlights the role of laser texturing in interface engineering rather than bulk transport enhancement.

3.1.3. Laser cutting

The first studies on laser cutting of battery electrodes date back to the early 2010s, when the growing demand for high-performance

LIBs highlighted the limitations of conventional mechanical cutting and punching techniques. Since then, as presented in Section 2, significant progress has been achieved, driven by the availability of high-quality laser sources, advances in beam delivery optics and scanning systems and an improved understanding of laser–material interactions. Today, laser cutting is widely adopted for high-speed processing of both bare aluminum and copper foils used as CCs, as well as coated CCs forming the electrodes. Cutting speeds of up to 30 m/s can be achieved for linear processing of CCs, while roll-to-roll electrode manufacturing typically operates at web speeds of around 3 m/s. The same system configuration is used for both electrode and CC cutting, as illustrated in Fig. 13. These operations are generally performed in-line within roll-to-roll systems, with the laser operating in an "on-the-fly" mode on the moving substrate. Fig. 14 presents the main cutting operations performed: (i) notching is applied to CCs to form tabs; (ii) slitting is used to separate electrodes during roll-to-roll processing; (iii) separation (nesting) defines the final electrode geometry that will be assembled into the cell. Laser cutting is primarily employed during the electrode fabrication (EP in Table 1). The following sections provide an overview of its application to both current collectors and electrodes, considering NIR and green laser sources operating in CW and PW regimes.

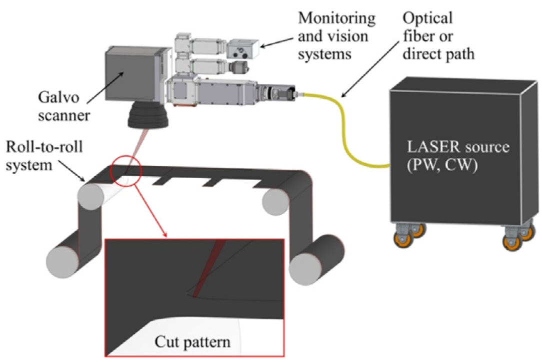

Fig. 13. Schematic of a laser-based cutting process in a roll-to-roll system.

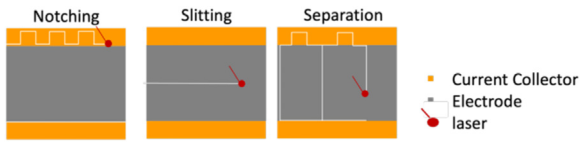

Fig. 14. Schematic representation of the main laser cutting operations in battery manufacturing: (left) notching of current collectors (CCs) for tab shaping, (center) slitting of electrodes in roll-to-roll processing and (right) separation for defining the final electrode geometry.

3.1.3.1. Laser cutting of current collectors. Current collectors play a key role in lithium-ion batteries by ensuring efficient current transport between electrodes and external circuits. Improving their electrical conductivity, reducing contact resistance and enhancing corrosion resistance directly benefits battery capacity, rate capability and cycle life [240]. As CCs are electrochemically inactive and currently account for ~15% of total cell weight, reducing their thickness (typically 6–30 μm for Cu and Al foils in automotive applications) is an effective strategy to increase overall energy density. Early studies mainly investigated PW lasers operating in the NIR and green spectral ranges, while recent work has demonstrated significant progress with high-quality single-mode CW fiber lasers with small delivery fiber cores (14–20 μm) [2].

A comprehensive comparison between CW and PW laser cutting of aluminum and copper CCs, at speeds up to 28 m/s, shows clear differences in performance. CW lasers provide higher productivity and better cut quality at high speeds. In contrast, PW lasers perform better at low cutting speeds ($\leq$4 m/s), especially for copper. Under these conditions, PW lasers produce less dross and smoother edges due to lower irradiance levels [2]. Similar trends were confirmed in [5]: CW cutting results in lower dross formation at high speeds, particularly for aluminum. In contrast, PW lasers provide greater robustness at lower speeds. However, they are more sensitive to atmospheric contamination, especially when processing copper. Typical cutting defects such as spatter, burrs, dross, recast layers and micro-cracks, have been systematically identified and linked to process parameters [12]. Progress has also been achieved in process understanding and quality control. Numerical models for CW cutting of aluminum and copper CCs, including coated foils, have shown good predictive accuracy for cutting speeds up to 5 m/s, supporting parameter optimization and industrial transfer [128]. In parallel, machine-vision and deep-learning approaches have been introduced for automated quality detection and geometric characterization of laser-cut edges, improving inspection reliability in production environments [122]. Additional studies demonstrated that ns green lasers (532 nm) can effectively cut ultra-thin copper foils (≈10 μm) with good kerf quality and speed [16]. Ultrashort-pulsed lasers (pulse duration <10 ps) represent a further technological advance. Their high peak power density enables material removal with minimal thermal diffusion. As a result, they produce nearly dross-free edges and significantly reduce the heat-affected zone (HAZ) [35]. Continuous power scaling of these sources, with average power doubling approximately every three years and repetition rates reaching tens of MHz, has significantly improved their ablation capability [221]. Pulse-burst strategies have further enhanced ablation efficiency and surface quality by reducing effective fluence while maintaining average power [234]. Picosecond lasers have demonstrated reduced HAZ and cutting speeds up to 3.8 m/s for copper CCs [96]. In addition, optimized low-fluence regimes have further improved cut quality and increased the maximum achievable speed for both Al and Cu foils [84]. Despite their superior quality, the industrial adoption of ultrashort-pulsed lasers remains limited. This is mainly due to lower throughput and higher system and environmental complexity. In summary, laser cutting of CCs has reached industrial maturity primarily through high-power, single-mode CW fiber lasers. These systems enable high-speed and high-quality processing of thin aluminum and copper foils. Pulsed wave lasers remain advantageous at low cutting speeds and for more challenging materials. Ultrashort-pulsed lasers, in contrast, offer the highest edge quality and minimal thermal damage, but are currently limited by throughput. Overall, laser source selection defines distinct performance regimes. Continuous wave lasers support industrial scalability, while pulsed and ultrashort-pulsed lasers are better suited for quality-driven applications.

3.1.3.2. Laser cutting of electrodes. Laser cutting of battery electrodes is a non-contact and highly flexible manufacturing process that avoids tool wear, making it an attractive alternative to mechanical die cutting [93]. However, as a thermal process, laser cutting is prone to defects such as kerf width irregularities, HAZ, burr formation [124], delamination and contamination, all of which strongly depend on process parameters [105]. Consequently, a substantial body of research has focused on understanding laser–material interactions to improve cut quality and mitigate these defects. Early comparative studies between CW and PW laser cutting demonstrated clear differences in achievable speeds and cut quality. While CW lasers enabled higher cutting speeds, PW ns lasers offered better control of clearance width at lower speeds. Subsequent work established quantitative links between process parameters and defect formation. For instance, correlations between HAZ extension and pulse characteristics were first reported in [188], showing that increasing pulse duration can reduce HAZ in graphite anode cutting. Systematic DOE-based studies further clarified the influence of laser parameters on kerf quality for both graphite anodes and NMC cathodes using ns Yb:YAG fiber lasers [134]. Material- and wavelength-dependent effects have also been extensively investigated. Studies on LFP and graphite-coated electrodes revealed that excessive pulse energy can induce chemical degradation of cathode materials and structural disorder in graphite anodes [155]. Comparisons between NIR and green ns lasers showed that green wavelengths generally yield higher cut quality on cathodes, particularly when operating at fluence levels that maximize metal ablation efficiency [150]. It was further shown that different cathode chemistries require distinct fluence regimes, with nickel manganese cobalt oxide (NMC)-coated aluminum foils demanding significantly higher fluence than LFP coatings [140]. Similar analyses were reported for $LiCoO_2$-coated cathodes using NIR ns fiber lasers, with cutting speeds up to 5 m/s [127]. More recent studies have highlighted process-driven improvements. Optimized parameter selection enabled a strong reduction of spatter size (<10 µm) and delamination (<5 µm) for both anodes and cathodes [17]. It was also shown that cathode edge quality has a stronger impact on electrochemical performance than anode edges, mainly due to metallic spatter contamination at the laser–current collector interface [105]. The adoption of ultrafast lasers (fs–ps regime) further reduced thermal damage, eliminating anode delamination during multi-scan cutting and enabling cutting speeds up to 3.8 m/s for graphite anodes [17]. Most recently, burst-mode operation has emerged as a promising pathway to combine high quality with increased productivity. GHz burst-mode cutting reduced effective pulse fluence while maintaining average power, leading to higher cutting speeds and improved process stability [8]. Projections indicate that with laser powers around 300 W, single-pass cutting speeds up to 7.5 m/s could be achievable for electrode cutting [8]. To summarize, laser cutting of electrodes has evolved from feasibility studies to a well-understood, high-performance process. Continuous wave lasers dominate high-speed industrial cutting, ns PW lasers provide robust quality control at lower speeds and ultrafast and burst-mode lasers offer superior edge quality with reduced thermal damage. Future progress is expected to focus on combining these advances to simultaneously achieve industrial throughput and minimal defect formation.

3.1.4. *Laser cleaning of cells*

When a laser beam directly interacts with the surface of the substrate, the impurities and the substrate both absorb the laser energy. The primary methods of laser contamination removal are thermal and shock effects; the former comprise ablation, thermal stress vibration and crack extension mechanisms [95]. Exploiting this principle, cell welding is very often preceded by laser cleaning of the cell pole, with the function of removing contaminants, resulting from previous processes and preventing defects in the welded joints. In [223] the beneficial effects of surface cleaning on metals performed by ns PW lasers at high-speed are reported, and the process is considered mature for industrial application. Laser parameters for high-speed cleaning typically include pulse energies between 5 and 125 µJ and fluences in the range of 0.5–12 J/cm^2. Pulse overlap and scanning line overlap are usually maintained between 50% and 90% to ensure uniform surface coverage. For cell cleaning, the system configuration is analogous to that used for laser welding (see Fig. 15); the main difference lies in the laser source, which is typically a nanosecond pulsed laser.

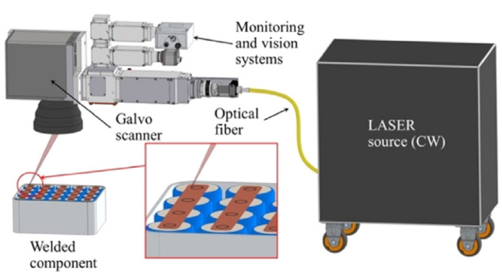

Fig. 15. Schematic of a laser welding process for battery module assembly.

3.1.5. *Manufacturing of batteries: laser welding*

Laser beam Welding (LBW) in the field of battery production has been applied for more than ten years in two main manufacturing fields: fabrication of cells (prismatic [197], cylindrical [3] and pouch [112]) and fabrication of modules or whole battery packs. In battery cell production, laser welding is used to join the internal foils that form the anode and cathode. It is also employed to connect these foils to the tabs, which act as the electrical terminals (positive and negative), and to seal the cell enclosure. Laser welding is also used to connect several cells in series and/or parallel to produce modules and/or final battery packs: connecting elements in the form of aluminum and/or copper thin sheets are used to "bridge" the different cells and/or the different modules. Fig. 15 shows the schematic of the laser welding process used for battery module assembly, where tabs are joined to cylindrical cells using a galvo-scanner-based system. The same laser configuration is also applicable to all laser-based processes in battery manufacturing, including battery case welding.

The welding of thin foils and module assembly operations can also be performed using ultrasonic welding processes. However, the non-contact characteristic of laser welding is particularly beneficial, since clamping systems in laser processes are less coercive compared to ultrasonic welding. Furthermore, the absolute freedom in programming the welding path given by the modern galvo scanners allows to fine tune and adapt the process to different scenarios, while ultrasonic welding is more limited given the need of a properly shaped sonotrode that fits the specific welding case. Regardless of the specific application, laser-welded joints must ensure both mechanical integrity and electrical performance. In particular, they must withstand vibrations and thermal fatigue typical of battery pack operation, while maintaining reliable electrical conductivity for efficient energy and power delivery over the service life.

3.1.5.1. Laser welding in cell fabrication. The studies summarized in Table 4 underline the increasing relevance of laser welding for electrical interconnections in battery cell manufacturing, particularly for joining stacks of ultra-thin metallic foils to tabs or busbars. A consistent trend emerges when comparing NIR and visible laser sources, especially for copper-based applications. Visible laser sources, namely green and blue lasers, exhibit superior process stability when welding highly reflective materials. As reported in [75], green laser welding of copper foil stacks provides enhanced stability compared to NIR solutions, with reduced penetration depth fluctuations, spatter and porosity, resulting in improved weld bead quality. Similar benefits are observed for blue lasers, which have been successfully applied to thin copper foils and thicker busbars [233], achieving electrical conductivity close to that of the bulk material, an essential requirement for battery applications. The applicability of blue lasers has also been demonstrated for stainless steel foil stacks [40], confirming their versatility in multi-layer thin-foil welding. Conversely, investigations on NIR sources [155] indicate that CW lasers outperform ns pulsed systems for both copper and aluminum, although weld bead porosity remains difficult to eliminate. The use of filler wire can mitigate porosity in aluminum joints [155], at the expense of increased process complexity. For aluminum tabs, long-pulsed fiber laser welding shows limited sensitivity of joint electrical resistance to process parameters, indicating a comparatively wider processing window [174]. Overall, visible laser sources emerge as a more effective solution for copper foil welding in battery cell fabrication, offering improved stability, weld quality and electrical performance. NIR

Table 4
Classification of recent contributions on laser welding for the production of cells.

Ref.	Laser source	Materials	Stack/geometry
[75]	Green/NIR	Copper	30 thin copper foils
[40]	Blue laser	Stainless steel	20 foils, 25 µm thick
[236]	Blue laser	Copper	40 foils, 10 µm thick; 230 µm busbars (lap and fillet)
[218]	Blue laser	Copper	30 foils, 9 µm thick on 0.2 mm copper tab
[158]	NIR (CW and ns-pulsed)	Copper	40 × 10 µm Cu on 3 mm Cu
[158]	NIR + filler wire	Aluminum	40 × 15 µm Al foils on 2 mm Al plate
[177]	Long-pulsed fiber laser	Aluminum	0.4 mm Al tab on 30 × 13 µm Al foils

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lasers remain suitable, particularly for aluminum, but often require additional process strategies to overcome porosity-related limitations, supporting the growing industrial adoption of visible-wavelength laser technologies.

3.1.5.2. Laser welding in module/pack fabrication. Laser welding configurations for battery module and pack interconnections strongly depend on cell geometry (see Table 5). For cylindrical cells, thin copper busbars (0.2–0.5 mm) are typically welded directly onto the steel can [23]. Pouch cells adopt either tab-to-tab or tab-to-busbar configurations, while prismatic cells generally involve busbar-to-tab welding with larger thicknesses, reflecting their higher energy and power density [187].

Table 5
Classification of recent contributions on laser welding for the production of module/packs.

Cell type	Typical welding configuration	Main materials involved	Ref.
Cylindrical	Busbar-to-can (lap welding)	Cu busbar to steel can	[23]
Pouch	Tab-to-tab or tab-to-busbar	Cu tabs, Al tabs, Cu/Al combinations	[62,48]
Prismatic	Busbar-to-tab	Cu or Al busbar to cell tab	[190]

Consequently, the wide variability in materials, thicknesses and joint geometries requires many process variants to ensure adequate weld quality. A major challenge in these applications is dissimilar material joining, most commonly involving Al/Cu, Al/Steel, and Cu/Steel combinations. In Al/Cu joints, intermetallic compound formation due to material mixing can lead to high hardness and brittleness, as shown in [194]. Optimal joint performance is achieved under low-mixing conditions, suggesting brazing-like mechanisms were molten aluminum wets copper with minimal dilution. Another critical issue is the high reflectivity of copper at NIR wavelengths, with absorptivity below 5% at room temperature. This necessitates high power densities and small spot sizes to trigger keyhole welding, often combined with beam oscillation using fast galvo scanners to stabilize the molten pool [49]. To overcome these limitations, visible-wavelength lasers have been increasingly investigated. Green lasers increase copper absorptivity up to about 60%, enabling stable conduction-mode welding [56], while blue lasers further enhance absorptivity (>70%) and provide highly stable melt pools with reduced spatter [202]. Comparative studies confirm improved penetration depth control and process stability when using visible wavelengths instead of NIR radiation [173]. Since 2017, blue diode lasers emitting at 450 nm [11] (250–700 W) have demonstrated promising results in welding thin copper foils [216], leading to rapid power scaling up to 1 kW in 2019 [15] and recently to 6 kW [14]. Applications on cylindrical cell interconnections show improved penetration control and reduced intermetallic formation [46], while pouch cell tab welding benefits from conduction-mode welding in terms of bead smoothness and penetration control [169]. Despite these advantages, visible-wavelength technologies are not yet widely adopted in battery production, mainly due to higher costs, lower availability and the strong industrial confidence in mature NIR systems. Consequently, NIR laser welding remains the dominant technology in battery manufacturing. As summarized in Table 6, recent studies mainly employ multimode CW sources, although single-mode and pulsed lasers also deliver competitive results. Aluminum/copper lap joints with thicknesses of 0.2–0.5 mm are predominant, typically produced with linear weld beads. Joint characterization commonly includes metallography, electrical and mechanical testing, and intermetallic compound analysis. Beam shaping, both static (core/ring) and dynamic (wobbling or oscillation), is widely applied to improve melt pool stability, reduce spatter, and enhance joint quality, electrical performance, and mechanical strength, often in combination with high-brilliance lasers and galvo scanners.

Table 6
Classification of recent contributions on laser welding of materials for battery production performed with NIR laser sources. (CW-MM, CW Multi Mode source; CW-SM, CW Single Mode source; SBS, Static Beam Shaping (core + ring technology); DBS, Dynamic Beam Shaping (beam oscillation technology); S-PW, Short-Pulse source (ns range); L-PW, Long-Pulse source (millisecond range); IMC, Inter-Metallic Compound detection).

Ref.	CW-MM	CW-SM	SBS	DBS	S-PW	L-PW	Material(s) - Joint type	Thickness [mm]	Weld bead shape	Joint characterization
[181]		X		X			Al/Cu - butt	1/1	Linear	Electrical test, IMC
[229]	X						Al/Cu - lap	1.6/1.6	Linear	Metallography, IMC, Tensile test, Hardness test
[148]				X		X	Cu/Al - lap	0.4/0.4	Linear	Metallography, tensile test
[133]						X	Al/Cu - lap	0.45/0.3	Linear	Metallography, Tensile test, Hardness test, Electrical test, Thermal test
[230]	X						Al/Cu - lap	1.6/1.6	Linear	Metallography, Tensile test, Hardness test, IMC
[6]					X		Al/Cu - lap	0.4/0.3	Linear, spiral spot	Metallography, Tensile test
[243]					X		Al/Cu - lap	0.2/0.2	Filled-in spot (spiral, concentric circles, parallel lines)	Metallography, Tensile test, IMC
[171]	X						Cu/steel - lap	0.2/0.3	Circular	Metallography, Electrical test, Tensile test, IMC
[48]	X			X			Cu/Al - lap	0.35/0.45	Linear	Metallography, Tensile test, Electrical test, IMC
[32]		X		X		X	Al/Al - lap	0.5/2	Circular	Metallography, -tensile test
[7]	X						Cu/Stainless steel - lap	0.24/0.5	Linear	Metallography, Electrical test, Tensile test, Hardness test
[50]							Cu/Al - lap	0.3/0.45	Linear	Metallography, Tensile test, Electrical test, IMC
[28]		X		X			Steel/Al - lap	0.25/3	Linear	Metallography, Tensile test, Electrical test, Hardness test, IMC
[101]	X		X				Steel-Al - lap	1/3	Linear	Metallography, Tensile test, Grain size, IMC
[207]				X		X	Al/Cu - lap	0.2/1	Linear	Metallography, Tensile test, Electrical test, IMC
[144]						X	Al/Cu - lap	0.4/0.4	Linear	Metallography, Electrical test, Tensile test, IMC
[65]	X	X	X				Cu/steel 0.4 + 0.4	0.4/0.4	Linear	Metallography
[53]	X						Al/Cu - lap	0.2/0.0.2	Spiral spots	Metallography, IMC
[202]	X		X				Al/Cu - lap	0.5/1	Linear	Metallography, Tensile test, Electrical test, Hardness test
[135]	X		X				Al/Cu - lap	0.5/0.0.5	Linear	Metallography, Tensile test, Electrical test
[204]	X						Al/Cu - lap	1/1	Linear	Metallography, Tensile test, IMC
[196]	X						Al/Cu - lap	1/1	Circular	Metallography, Tensile test, Dilution
[127]	X			X			Cu/Steel - lap	0.5/0.3	Linear	Metallography, Tensile test, Electrical test
[1]	X				X		Al/Cu - lap	0.75/1.5	Linear	Metallography, Hardness test, electrical test, Tensile test, IMC
[54]	X						Al/Cu - lap	0.2/0.2	Spiral spots	Metallography, Tensile test, IMCl

3.1.5.3. Laser welding of battery cases. In high-volume production, aluminum battery casings are typically used for long-range BEVs (those with a range of more than 250 km before needing to recharge). According to a survey presented at the Automotive Circle EALA2020 [63], there is a 30% preference for adopting 6xxx aluminum alloys to create more cost-effective and lighter battery casings, with laser welding being an emerging joining method, currently being investigated as an alternative solution to more established processes, such as friction stir welding and Cold Metal Transfer (CMT)/MIG. When applied to 6xxx aluminum alloys, the laser welding technology is hindered by a few challenges [198]: (i) weld porosity—pores trapped in the melting pool can diminish weld strength, durability, and water/gas tightness. (ii) Part-to-part gaps—manufacturing tolerances can lead to unwanted gaps between parts. With extruded profiles, the standard form tolerance is ±0.8 mm over a meter length and, if not properly controlled, these gaps can reach up to 1.6 mm [138]. (iii) Weld solidification cracks—with no doubts, they represent a major burden that severely limits applications of laser welding [134]. The state-of-the-art approach, known as wire-fed laser welding with proximity heads, uses a laser in conjunction with filler wires (i.e., 4043 aluminum wires) to change the chemical composition in the fusion zone and modify the solidification path, hence reduce crack sensitivity, help bridging part-to-part control weld porosity [111]. Successful reports have developed solutions for typical thicknesses in the range of 2 to 5 mm, with fillet lap joint geometry and wire diameter >1 mm. The systems of choice are NIR multi-kW CW lasers with spot diameters of 600 µm [137]. Recent research has focused on alternative approaches for welding aluminum extruded profiles, including beam oscillation, power modulation, and beam shaping. Combining beam oscillation with power modulation enables gap bridging and higher welding speeds while reducing laser power. Typical setups use a ~200 µm spot oscillated at high frequency to tailor heat input and achieve desired weld properties. This approach can bridge gaps up to 45% of the part thickness and increase shear strength by up to 70% at production-relevant speeds (4.8 m/min) [138], while also reducing thermal deformation. The work in [149] demonstrated that active cooling, together with the welding and clamping sequence, plays a key role in achieving the dimensional and geometrical quality of the case.

3.2. Energy storage systems: manufacturing of fuel cells

Fuel cell manufacturing mainly involves laser-based operations on BPs. In this context, LBM is applied both for shaping and joining thin metallic plates, and for modifying surface properties to improve functionality. The following paragraphs therefore focus on two main process families: laser cutting and welding of BPs, and laser structuring/texturing for enhancing water management, corrosion resistance, and adhesive bonding.

3.2.1. Laser cutting and welding of bipolar plates

The production cycle of metallic starts with sheet forming through stamping, hydroforming, rubber forming, or roll forming. The plates must be coated with a protective layer to prevent chemical degradation; the final process step is the joining of the single sheets to generate the functional bipolar plate. Forming and laser cutting of pre-coted metallic sheets is of great interest to increase manufacturing throughput, in [156] the effects of laser cutting of AISI 316 L sheet coated with Graphite Like Carbon (GLC). Laser cutting is employed to create a central gas outlet and to trim the outer border of the preformed plate, the contaminants created during laser processing appear to shorten the operating life of the FC. Laser welding is the natural choice for joining thin metallic plates along complex paths. The small thickness of the metallic foils promotes the use of pulsed laser; the only constraints concern the decreasing of the corrosion resistance due to the chemical and microstructural modifications induced by phase changes. Fig. 16 shows a schematic of the laser system configuration, which can be applied to cutting, welding and structuring processes for fuel cell bipolar plate manufacturing.

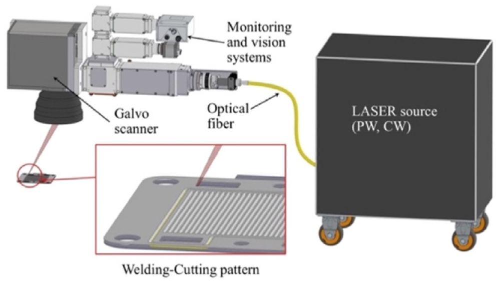

Fig. 16. Schematic of laser-based cutting, welding and structuring processes for fuel cell bipolar plates.

A correlation between laser parameters and corrosion resistance in ms pulsed laser welding is reported in [163]. The results indicate that maintaining pulse energy and pulse duration just above the welding threshold is key to minimizing corrosion issues. The use of ns pulsed lasers is demonstrated in [78]. In this case, reducing power during full penetration welding is necessary to avoid defects such as humping and foil warpage. Effective strategies include beam wobbling and beam tilting. The use of QCW green lasers is presented in [79]. These lasers simulate CW operation by emitting ns pulses at high repetition rates (~0.2 GHz). The combination of QCW operation and higher absorptivity at shorter wavelengths enables welding speeds up to 2 m/min. Another approach to reduce deformation in thin foils is multi-pass welding [235]. In this method, each bipolar plate (BP) channel is sealed using multiple weld seams, with optimized pass sequence and direction. In fuel cell production, welding of thin bipolar plates requires small spot sizes (<50 µm) and moderate power levels (<1 kW). In this context, QCW lasers offer advantages in terms of increased welding speed.

3.2.2. Laser structuring of fuel cells bipolar plates

Laser structuring and patterning are promising technologies for improving PEMFC performance. These processes aim to achieve three main effects: increasing surface roughness (and thus active area), enhancing water drainage, and improving the strength of adhesive joints in chemically sealed bipolar plates (BPs). Early studies focused on enhancing water transport through laser micro-drilling of gas diffusion layers (GDLs) [70]. Using Nd:YAG lasers, holes of about 80 µm were created. The non-contact nature of the process reduces the risk of damaging the membrane with broken carbon fibers. In addition, the high aspect ratio of the holes preserves contact area and electrical efficiency. Laser perforation has since been successfully validated at laboratory scale, demonstrating improved PEMFC performance and stability [71]. Water management can also be improved by direct laser structuring of stainless-steel BPs [228]. In this case, laser processing combined with graphitization can induce stable superhydrophobic surfaces and significantly increase corrosion resistance. BP surface structuring typically relies on short and ultrashort pulsed lasers. These processes require relatively low power (<1 kW) but high repetition rates to ensure high-speed processing over large areas. Ultrafast lasers enable the formation of Laser-Induced Periodic Surface Structures (LIPSS) at sub-micron scale. This allows surface modification without damaging the underlying coating. For example, superhydrophobic behavior has been demonstrated on TiN-coated SS304 plates [45]. The low thermal impact of ultrafast lasers also improves process stability. Picosecond lasers have shown high robustness when micro-drilling commercial GDLs, even in the presence of binders and porosity variations [69]. Finally, laser texturing can significantly enhance adhesive bonding in BPs. Studies on titanium plates show that ns laser texturing modifies surface topography and chemistry, increasing shear strength by more than a factor of two and promoting cohesive failure of the adhesive layer [148].

3.3. Drives

Electric drive manufacturing relies on a sequence of forming, insulation removal and joining processes, where laser-based technologies play a key enabling role. The following paragraphs focus on laser stripping and welding of hairpins, highlighting the main process principles, technological solutions and associated challenges.

3.3.1. Electric drive architecture and manufacturing requirements

Commonly pure Cu grades (e.g., Cu ETP, Cu OF, Cu OFE) [160] are employed as the hairpin winding material while in some vehicles Al-alloys are employed for reducing weight [37]. The material is provided in coil form with an insulating barrier commonly composed on thermoplastic materials such as polyether ether ketone, polyester (amide)(imide), and poly(amide)(imide). The insulation is often composed of multiple material layers, with a total thickness typically around 0.1 mm [73]. The bars are uncoiled, locally stripped from the insulating layer, cut to the required length and bent to the required shape in automated lines [20]. The insulation removal can be effectively performed using laser processes. Compared to mechanical or chemical methods, laser-based stripping offers greater geometrical flexibility and process precision [190]. After this phase, the bars are bent and inserted in the stator inside the relative slots in the laminate stacks made of Fe-Si alloys [217]. Laminated electrical steel sheets are typically welded using laser sources operating in PW and CW mode, with pulse durations ranging from microseconds to milliseconds. Common solutions include Nd:YAG, fiber, and disc lasers [36]. Alternative approaches, such as blue laser sources [203] and laser welding under vacuum conditions [115] have also been proposed. To provide a complete electrical circuit, the open ends of the winding are required to be connected permanently [106]. Laser welding is the most common process used as it provides contact-free welds in a remote fashion. The process can execute each weld in the range of 0.1 and 0.4 s per weld depending on the hairpin size. The laser welding operation is often executed without a protective gas. The absence of protective gas is due to the difficulty in following the scanning laser beam with a local shielding nozzle. Nevertheless, the use of protective gas has provided only a limited benefit observed in terms of porosity reduction [158]. Geometrical inaccuracies and possible contaminations on the welded hairpin couples build up prior to the welding stage [60]. The welding process therefore is supposed to be robust enough to withstand such variations and ideally be tolerant to the errors [74]. In an electric drive stator for traction there can up to 200 hairpin couples to be welded. A single failed weld results in failure of the drive [238].

3.3.2. Laser stripping of hairpins

Laser stripping of hairpins is carried out commonly using PW laser sources [38]. The process should remove the polymeric enamel on the surface leaving only bare copper exposed for the successive welding operation [180]. The size of the stripped area depends on hairpin geometry and the heat-affected zone from welding. Pulsed lasers (µs–ns) across IR, NIR, visible, and UV wavelengths are used. The wavelength governs the interaction mechanism, determining whether the laser is absorbed at the surface, within the coating, or transmitted to the underlying metal [25]. The use of CO_2 lasers typically operating at 10,600 nm with µs-long pulses allows for absorption from the surface resulting in a vaporization dominant material removal mechanism [151]. Active fiber and disc lasers operating in the range of 1030–1070 nm are employed with ns-long pulses produce an indirect absorption mechanism removing material by partial ejection from the bulk as well as conduction-based heating from the copper layer [181]. Green light can provide a relative improvement in the absorption behaviour. The use of UV wavelengths using the same laser sources at the third harmonic between 343 and 357 nm can induce absorption from the material surface providing an ablation-based process [232]. Both visible and UV wavelengths are operated with ns-long pulses. Being based on a surface cleaning process, the main aim of laser stripping is the complete material removal in depth rather than strict geometrical precision in the scanned plane. A complete material removal in depth may not be possible due to the variation of the optical absorption properties as the material is removed [25]. The residual polymer vaporizes rapidly during the welding process, getting entrapped in the molten pool [72]. The resultant weld bead may be characterized by excessive porosity leading to low mechanical properties. A possible approach is to combine laser stripping with a CO_2 laser followed by a fiber laser, which has been shown to be advantageous [39]. Pulsed wave laser sources are more widely available in industry than CW sources, as they are used across a broader range of applications that typically require relatively low average power levels (1–100 W). Laser stripping can be performed using a process configuration similar to that shown in Fig. 17.

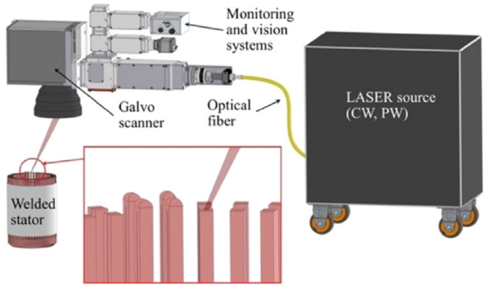

Fig. 17. Schematic description of the laser hairpin processing system, where PW lasers are employed for hairpin stripping and CW lasers are used for hairpin welding.

3.3.3. Laser welding of hairpins

Laser welding of hairpins is typically carried out in a remote welding configuration using CW multi-kW disc and fiber laser sources. Fig. 17 shows the typical system configuration adopted for this process in electric drive stators. The setup includes fiber delivery, scanner optics and integrated monitoring systems, enabling high-speed, non-contact joining of multiple hairpin terminals within the stator assembly. Laser beams with diameters in the range of 0.15–0.30 mm are commonly employed. In industrial applications, CW lasers with power levels between 3 and 8 kW represent the preferred solution.

Within this framework, the joining of hairpin ends is achieved through dedicated scan strategies. The open ends of the hairpin couples (Fig. 18a) can be jointed with different scan strategies [241] which can follow closed paths (e.g., circle, ellipse, infinity) [231] or discrete patterns (e.g., lines, dots) [47] (see Fig. 18b). The process is typically based on keyhole welding. Repeated scans are used to enlarge the melt pool and ensure full coverage of the hairpin surfaces. After laser emission stops, the molten mat9rial solidifies, forming a characteristic bead shape driven by surface tension (see Fig. 18c). Keyhole stability is critical for process quality. Instabilities can lead to defects such as porosity and spatter [158]. Porosity reduces mechanical strength and increases electrical resistance. Spatter, in addition to affecting component cleanliness, may contaminate the optics, thereby degrading the quality of subsequent welds. Therefore, different laser solutions have been employed using different process parameter combinations [160], new wavelengths in the visible range [233], as well as beam shaping options [20].

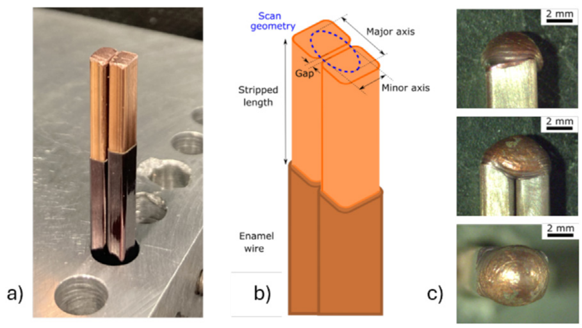

Fig. 18. a) Hairpin couples prepared for welding showing the stripped region and the cut flat surface. b) Schematic description of the weld scan trajectory in laser welding. c) The morphology of the weld bead.

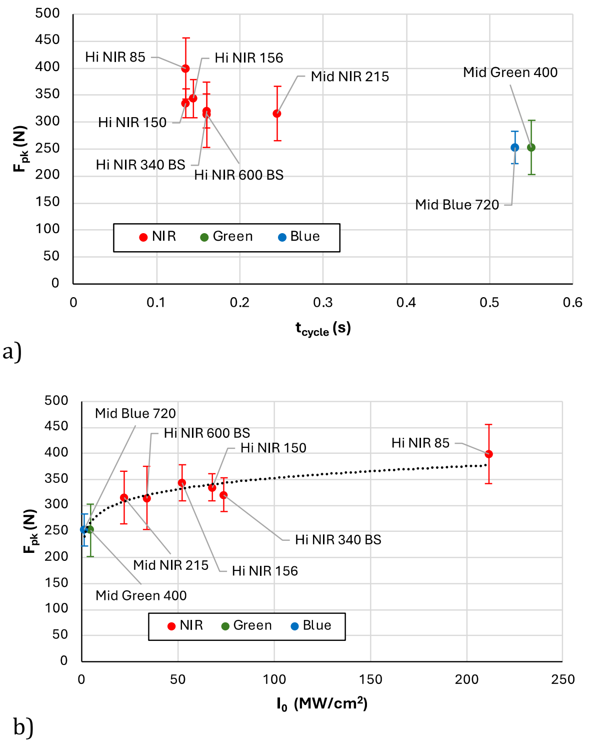

Fig. 19. Peak force to rupture as a function of (a) cycle time, and (b) peak irradiance [41]. The data tags indicate the qualitative power level categories (Mid-High) along with table he wavelength (NIR, blue, green) and the beam size in micrometers.

Although the benefit of green lasers for improved weld depth has been shown in linear weld trajectories [110], concerning hairpin welding, the results showed that the use of a green laser does not provide an increase in productivity [39]. This is likely due to the wide melt pool formed during hairpin welding. The molten material absorbs NIR radiation more effectively than the solid phase. Commercial NIR lasers operate at high power and small spot sizes, enabling shorter cycle times. This makes them the preferred choice for hairpin welding applications. The use of core/ring configurations appears to reduce spatter formation both with NIR [237] and green laser sources [109]. For single-mode cores with ring beam profiles, higher magnification factors are used. This increases the focal length of the focusing lens, allowing a greater working distance to cover larger areas and reduce spatter. These conditions enable welding of the entire stator within the scanner field. Coherent beam combining at NIR wavelength is a recent approach for generating tailored beam profiles, currently under investigation to reduce porosity and spatter in copper hairpin welding [177]. The use of high power (3 kW) blue laser with relatively large beam size (720 µm) has been shown to produce conduction mode welds on hairpins with the expense of long processing times [162]. Blue lasers can be exploited for welding thinner hairpin couples in conduction mode, potentially reducing spatter. Hybrid solutions combining blue diode and high-brilliance NIR lasers have also been proposed, where the blue beam enhances absorptivity and the NIR beam provides high intensity. Fig. 19 compares different laser sources for welding copper hairpins in terms of productivity (cycle time t_{cycle}, in Fig. 19a) and mechanical strength (peak force in tensile tests F_{pk}, in Fig. 19b).

Peak irradiance (I_0) is used to compare processing conditions. Results show that the highest mechanical strength is achieved at maximum productivity with high-intensity beams. Weld strength depends on bead size, internal defects and HAZ. However, bead size alone can be misleading, as porosity reduces the effective contact area. Keyhole welding often traps pores at the bead bottom. High-intensity beams improve productivity, reduce processing time and thermal damage and increase joint strength. Higher speeds also enhance strength by limiting melt pool exposure and HAZ size. Gap and misalignment are common issues in the industrial practice [160]. If the beam passes through gaps, vaporized insulation can cause spatter or porosity. This can be mitigated through trajectory corrections that avoid gap regions.

3.4. *Limitations and open challenges*

The above-mentioned analysis shows a wide variety of laser-based processes currently applied to EV manufacturing. Table 7 shows an overall comparison of the most important process parameters characterizing the different technologies analysed so far suitable for industrial-scale production. The different ranges in terms of laser power, energy and process speed give an idea of the current state of the art in the different applications.

Table 8 highlights differences in maturity across processes, showing that many limitations are process-specific rather than technology-driven. While cutting, welding and stripping are industrially mature, processes such as drying, structuring, perforation, and texturing remain constrained by throughput, scalability, and integration. Common challenges include limited production speed, sensitivity to material variability, lack of standardized quality metrics, and insufficient closed-loop control. Although laser systems offer high flexibility, they also increase complexity in selection and integration. Overall, future progress will depend more on system-level solutions—such as parallelization, robustness, in-line monitoring, and cost-effective integration—than on new laser technologies.

Table 7
Summary of laser parameters: “not used” or “rarely used” refers to their applicability in industrial-scale production.

Processes	CW NIR		CW Visible		PW NIR		PW Visible	
	Power	Speed	Power	Speed	Power/ Energy	Speed	Power/energy	Speed
Welding (electrical contacts)	500–1500 W	50–500 mm/s	500–1500 W	50–500 mm/s	50–300 W	100–300 mm/s	Rarely used	Rarely used
Welding (hairpins)	3000–6000 W	100–300 mm/s	2000–6000 W	50–200 mm/s	Not used	Not used	Not used	Not used
Cutting (current collectors)	400–1200W	Up to 30 m/sec	Rarely used	Rarely used	20–300 W	Up to 20 m/sec	Rarely used	Rarely used
Cutting (electrodes)	200–2000 W	Up to 5 m/s	Rarely used	Rarely used	Up to 300 W	7.5 m/s	Up to 50W	Up to 3,8 m/sec
Stripping (hairpins)	Rarely used	Rarely used	Rarely used	Rarely used	50–1000 W	2–5 cm^3/min/kW	10–100 W	1–3 cm^3/min/kW
Structuring (electrodes)	Not used	Not used	Not used	Not used	10–15 W (cathode)	0.2–1 MHz	10 J/cm^2 (anode)	200 kHz (80 pulses/hole)
Drying (electrodes)	Up to 8 kW	318 g/(m^2s^{-1}) drying speed	Not used	Not used	Not used	Not used	Not used	Not used
Cleaning	Not used	Not used	Not used	Not used	5–125 mJ	0.5–1.2 m/s	Not used	Not used

Table 8
Unified overview of LBM processes for EV components.

Laser-based process	Main EV components	Process objective	State Of industrial maturity	Key benefits	Main limitations	Key R&D needs
Laser drying	LIB electrodes	Accelerated solvent removal	Pilot/pre-industrial	Reduced drying time, lower energy use, smaller footprint	Binder migration, local overheating	Hybrid laser–convection systems, inline thermal control
Laser structuring	LIB electrodes, SSB interfaces	Create diffusion pathways	Laboratory/pilot	Improved ion transport, rate capability, energy density	Very low throughput, high cost	Multi-beam architectures, roll-to-roll integration
Laser perforation	LIB electrodes	Through-hole diffusion paths	Laboratory/pilot	Enhanced high-rate performance	Limited scalability	Parallel drilling strategies, cost analysis
Laser cutting	Electrodes, current collectors	Shaping and separation	**Industrial**	High speed, precision, no tool wear	Edge defects especially at low speed	Adaptive control, inline quality metrics
Laser cleaning	Tabs, CCs, interfaces	Contaminant removal	Near-industrial	Improved weld quality and wettability	Limited standardization	Closed-loop cleaning validation
Laser welding	Hairpins, tabs, busbars, bipolar plates	Electrical and mechanical joining	**Industrial**	Automation-ready, high reliability	Sensitivity to gaps and variability	Self-adaptive welding, defect tolerance
Laser stripping	Hairpin insulation	Selective insulation removal	**Industrial**	Non-contact, geometry flexibility	Residual insulation risk	Inline verification systems
Laser surface texturing	CCs, fuel cell bipolar plates	Interface and surface control	Pre-industrial	Improved adhesion, wettability, contact resistance	Area rate, uniformity	High-throughput texturing systems
Laser additive manufacturing	Electric drive parts	Near-net-shape fabrication	Emerging	Design freedom, functional grading	Cost, productivity	Hybrid AM–subtractive chains

4. Process monitoring and control

Ensuring robust and scalable laser-based manufacturing in EV production requires advanced monitoring and control strategies capable of addressing process variability and high-speed dynamics. The following sections review the main sensing technologies and control approaches currently adopted to enable in-process quality assurance and predictive data-driven manufacturing.

4.1. Overview

Although several laser-based technologies are established in industry, a significant gap remains between laboratory validation and high-volume EV manufacturing. Many processes perform well under controlled conditions but struggle to achieve the required robustness, repeatability and scalability in gigafactories. This gap is critical in EV production, where tight tolerances demand micron-level accuracy, consistent penetration, and controlled electrical resistance. As a result, quality assurance in LBM is undergoing a fundamental transition. Post-process inspection methods are no longer viable at current production volumes and takt times. As a result, the industry is shifting toward in-process detection and control, enabled by advanced sensing and data-driven approaches, while manufacturing evolves toward intelligent systems. This transition is driven by Industry 4.0 tools [108] including Machine Learning (ML) [27], Artificial Intelligence (AI) and computer-aided physical simulations [33]. Those tools have the potential to improve productivity and quality, optimize energy consumption and reduce scrap. This evolution can be broadly classified into three stages. **First**, in-process defect detection with post-process repair, where ML classifiers identify defective parts with accuracies approaching 95–97%, enabling targeted rework. **Second**, pre-process defect detection with predictive adjustment, where sensors such as laser triangulation detect part-to-part gaps or misalignment and adjust process parameters accordingly. **Third**, in-process defect detection with predictive control, where high-frequency sensor data anticipate instabilities and allow proactive parameter adjustment. The last stage is currently the main focus of research, with encouraging laboratory results. Its effectiveness depends strongly on the spatial and temporal resolution of monitoring and control systems. From a spatial perspective, features can be divided into surface and sub-surface. Surface features include melt pool width, bead continuity, and geometry. Sub-surface features include penetration depth, interface width, porosity and cracks. Surface features can be measured using CMOS/CCD cameras or laser sensors. In contrast, in-process measurement of sub-surface features remains largely unresolved. This is critical in EV battery manufacturing, where undetected defects may lead to leakage, short circuits, or thermal runaway. Temporal resolution is equally important. Laser–material interactions evolve on extremely short timescales. In keyhole welding, vapour jets reach 5–250 m/s, while molten pool flow is 0.1–1 m/s. Keyhole dynamics and heat transfer can change within microseconds, and solidification occurs in milliseconds. These dynamics limit conventional control strategies. For instance, keyhole collapse originates from instabilities due to changes in absorptivity, contamination, or thickness variation. Although the defect becomes visible only after collapse, the instability develops earlier, over millisecond-to-second timescales. This creates a critical window that predictive ML approaches can exploit. Worth noting that although high-speed X-ray imaging [82] offers unparalleled spatial and temporal resolution for observing keyhole dynamics and pore formation, its application remains largely confined to offline process characterization (laboratory process development) due to cost, safety and system integration constraints. Sections 4.2, 4.3 and 4.4 report the latest trends in process monitoring and control used in LBM EV production.

4.2. Optical coherence tomography

Latest advancements in Optical Coherence Tomography (OCT) have shown promising results towards direct measurement of weld penetration depth (Fig. 20 shows typical OCT signals). With OCT, light from a low-coherence source is split into two beams. The process beam travels along a reference path, while the second one (measuring beam) propagates through the welding head into the keyhole. The difference in optical path length generates an interference pattern, from which distance information is extracted based on the detected signal frequency [18]. In [126] a in-process monitoring

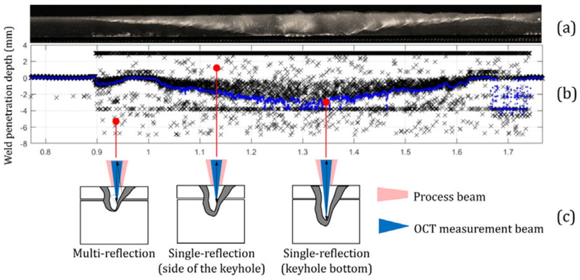

Fig. 20. Typical signal generated by OCT technology. (a) longitudinal cross-section; (b) OCT signal; (c) schematics.

based on the adoption of a laser line was applied for the in-process defect detection. In [52] it was shown that accurate OCT measurements require precise alignment of the probing beam with the keyhole bottom. However, maintaining this alignment is challenging due to dynamic variations in keyhole geometry. OCT has also been combined with core/ring lasers for battery tab welding (450 µm Al to 300 µm Cu) [64]. The system measured penetration depth with an accuracy within 100 µm compared to metallography. Accuracy was highly sensitive to process parameters but improved by ~50% using core/ring configurations. This highlights a strong link between process stability and OCT performance, influenced by keyhole geometry and internal reflections.

4.3. Photodiode-based monitoring

The sensitivity to process parameters can be overcome by photodiodes that have a simple structure and can be retrofitted to any laser-based production equipment. They allow sensing the radiation from the metal vapor and plasma plume (S_P signal), the thermal condition of the processed zone (S_r signal) and the reflected laser light (S_R signal). The three sensors detect the radiation in three distinguished bandwidths. For process laser beams emitting in the NIR, the typical bandwidths are: S_P sensor − 300−700 nm; S_R sensor—1020−1090 nm; *Sr* sensor—1200−2000 nm. Authors in [129] applied machine learning techniques to classify weld penetration using photodiode signals. They used a support vector machine and two neural networks: a fully connected network and a convolutional neural network. A dataset of 405 samples was collected and split into training (283), validation (61) and testing (61) sets. The models predicted penetration states (unsatisfactory, transient or good) every 50 ms, achieving classification accuracies above 90%. The convolutional neural network (CNN) was further validated experimentally by varying laser power, confirming its effectiveness in estimating Al/Cu weld penetration. In addition, variations in part-to-part gap and laser power can be identified through step changes in plasma signals, as reported in [33]. Fig. 21 illustrates representative plasma signals with varying part-to-part gap. The effectiveness of photodiodes combined

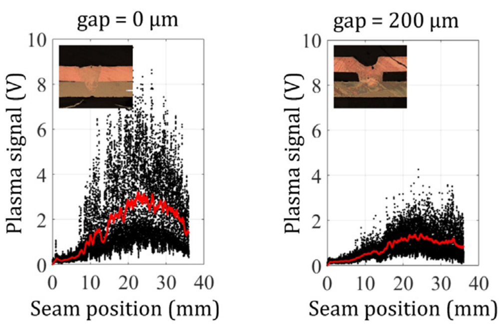

Fig. 21. Example of plasma signals during in-process monitoring using photodiodes.

with supervised ML algorithms was investigated for automatic classification of weld defects. The study focused on defects caused by simultaneous variations in part-to-part gap and laser power during remote welding of copper-to-steel battery tabs. The results showed a classification accuracy of 97%, which appears highly promising. However, in high-value manufacturing contexts, this level of accuracy may still be insufficient. In a battery pack with 20,000 welds, a 3% error rate would correspond to approximately 500 misclassified welds. The study also highlights that classification performance improves with increasing dataset size. Most existing works rely on small to medium datasets, typically containing 100−200 samples. Model performance is commonly evaluated using leave-k-out cross-validation, with a 70/30 split between training and validation sets to avoid underfitting and overfitting. There is general agreement that larger datasets are essential to improve model accuracy and generalization. However, acquiring such datasets is costly, as defective samples must often be intentionally produced, leading to material waste. When scaling from a single battery pack to annual production volumes of hundreds of thousands of units, these limitations become more critical. This highlights the need for further research on ML algorithms and process causality to enable reliable, data-driven laser manufacturing systems.

4.4. Acoustic-based monitoring

Recent advancements in membrane-free optical microphones [205] represent an interesting solution for in-process monitoring of product defects and arguably can offer a valid complement to the well-established photodiode-based monitoring. This acoustic sensing approach operates without a vibrating membrane and covers a wide frequency range (10 Hz to tens of MHz), enabling clear separation between process signals and noise. It is based on a cavity with semi-reflective mirrors [171] where a measurement laser detects pressure-induced refractive index changes caused by acoustic emissions during welding. These emissions originate from laser−material interaction, keyhole dynamics and vaporization. Low-frequency signals are associated with instabilities and melt pool flow, while high-frequency components relate to rapid phase transitions and microstructural changes [58]. In [85], real-time weld defect detection in battery cell production was achieved by correlating acoustic and photodiode signal features with intentional defects, demonstrating effective in-situ quality monitoring. Similarly, [159] showed that acoustic emissions in the 10−800 kHz range during hairpin welding correlate with weld geometry and enable detection of defects such as spatters. The findings showed that higher acoustic energy correlated with increased cross-sectional areas of welds, while alterations in sound emissions effectively detected defects such as spatters. Applied to busbar-to-terminal connections, [13] showed a strong correlation between acoustic signals and key weld events, including lack of fusion, lack of connection, sound joints, and piercing. Optical microphones can distinguish the transition from blind to through keyhole. Despite these results, studies remain fragmented and lack validation across materials and industrial conditions, highlighting the need for further standardization and research.

4.5. Control systems in EV laser-based manufacturing

Traditionally, LBM control has relied on closed-loop PID controllers to regulate variables such as laser power and beam motion. These controllers are robust and widely used. However, they are inherently reactive and not well suited to the fast, stochastic dynamics of laser−material interactions in high-speed EV manufacturing. In such conditions, defects such as keyhole instabilities, porosity, and spatter can develop faster than the controller response, leading to irreversible defects. As a result, next-generation LBM systems are shifting toward predictive, ML-enabled control. High-frequency in-situ sensor data (such as photodiode signals, high-speed imaging and acoustic emissions) are analyzed to detect early signs of instability before defects become visible. The extracted features are then processed using different ML techniques. Convolutional neural networks (CNNs) are used for image-based defect detection [22]. Recurrent neural networks (RNNs) are applied to time-series data analysis [132]. Reinforcement learning is used for adaptive control of laser parameters [144]. In practice, ML acts as a supervisory layer on top of conventional PID control. The PID loop ensures millisecond-scale reactive stability, while ML anticipates disturbances and adapts setpoints or controller gains proactively. Such hybrid architectures enable closed-loop, self-optimizing laser processes. These are essential to meet the stringent quality, productivity and safety requirements of next-generation EV manufacturing. Sensor selection, ML architecture and control strategy must be tailored to both process scale and temporal dynamics [139]. Microsecond-scale monitoring is required for high-speed processes, while millisecond-scale is sufficient for module or pack operations. Understanding this is key for real-time predictive control. At the cell level, laser speeds exceed 1000 mm/s, leading to µs-scale dynamics. Early defects (e.g., pores, keyhole instability) occur within 1−100 µs, making CNNs suitable for capturing spatial features. At module/pack level, slower dynamics (1−10 ms) allow temporal analysis. Here, RNNs (e.g., Long Short-Term Memory) are more effective, although their performance is limited for ultra-fast processes due to insufficient temporal resolution.

5. Process simulation

The introduction of predictive and ML-enabled control systems into LBM for EV production offers major opportunities to improve quality and productivity. However, it also creates the need to optimize a very large number of process parameters. This remains a significant challenge. For this reason, advanced simulations of laser-based material processing are becoming increasingly important. Their adoption is supported by the growth of computational power and multi-core high-performance computing, and they are now used to complement laboratory testing. Laser−material interaction involves highly coupled physical phenomena. These include laser absorption, heat transfer, melt flow, fluid dynamics, vapor dynamics, phase transitions, phase transformations, and microstructure evolution [61]. To understand and predict these effects, modelling must consider multiple spatial and temporal scales. These are typically classified as macro-, meso- and micro-scales. At the macro-scale, modelling usually relies on thermo-mechanical approaches. In these models, the laser beam is represented as a moving heat source. The results provide the temperature history over time, as well as displacements, strains, and stresses. This allows analysis of the overall thermal and mechanical response of the component. At the meso-scale, the focus shifts to melt pool fluid flow and heat transfer. More advanced multi-physics models are used in this case. They describe the interaction between plasma, gas, liquid, and solid phases, and can capture keyhole dynamics, melt pool convection, recoil pressure, and surface evolution. At the micro-scale, modelling addresses phase transformations and microstructure formation. This includes solidification, grain growth, and the evolution of metallurgical features that determine the final mechanical and electrical properties of the processed material. In most cases, process simulation begins at the macro-scale with thermo-mechanical coupling. These models simplify the thermal problem, but they can still account for metallurgical transformations during heating and cooling. They are widely used to predict thermal stresses, strain evolution, and cooling rates in laser processing. Boundary conditions generally assume natural convective heat transfer, while thermal radiation is sometimes neglected because it is not the dominant mechanism. Material properties are usually temperature dependent and taken from databases. Since fluid flow is neglected, the numerical problem is significantly reduced, allowing simulation of entire components. In these models, the complex laser−material interaction is simplified into an equivalent volumetric moving heat source. The main difficulty lies in defining this equivalent source. This is usually done by calibrating simulation results against experiments, for example by matching

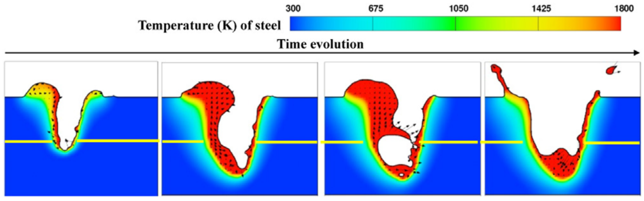

Fig. 22. Example of multi-physics CFD models used to predict keyhole dynamics during laser beam welding of Zn-coated steel [86].

weld profiles. Reported studies show errors below 10% for weld geometry prediction and below 5% for cooling rate estimation. Nevertheless, thermo-mechanical models are not fully predictive by nature, because they still require experimental calibration. Meso-scale simulation with *multi-physical simulation* of laser-based processes (Fig. 22) have evolved significantly in recent years, yielding accurate predictions. Virtually all published simulations involving meso-scale simulation with *multi-physical simulations* rely on simplifying assumptions to make the problem computationally manageable. Solid and liquid phases are typically treated as incompressible, neglecting density variations due to thermal expansion or phase change. Flow in the melt pool and vapor phase is often assumed to be laminar, as turbulence is uncommon in the small melt pools typical of laser processing.

Including turbulence would also significantly increase computational cost. The viscosity of the fluid phases is generally modelled as Newtonian, ignoring possible non-Newtonian effects that may arise under extreme temperature gradients or high strain rates. Although these assumptions reduce model fidelity in highly dynamic conditions, they enable simulations to capture the dominant thermal, fluid flow, and phase-change phenomena relevant to most laser-based manufacturing applications in EV production. Several studies demonstrate the capabilities of CFD and multi-physics modelling in laser processing. In [98], a CFD model was developed to analyze metal mixing during linear laser welding of 200 μm Al to 500 μm Cu, considering different laser powers and scanning speeds, with particular attention to recoil pressure and Marangoni effects. In [34], a multi-physics model was used to investigate the impact of beam shaping on metal mixing and molten pool dynamics during Cu-to-steel welding for battery connections (see Fig. 23). Similarly, [24] implemented CFD simulations with adaptive mesh refinement to predict weld seam geometry in the presence of part-to-part gaps and to evaluate the effect of secondary beam shapes. In [97], experimental results were combined with CFD simulations to study the influence of beam oscillation parameters on fluid flow and mixing in Al−Cu welding.

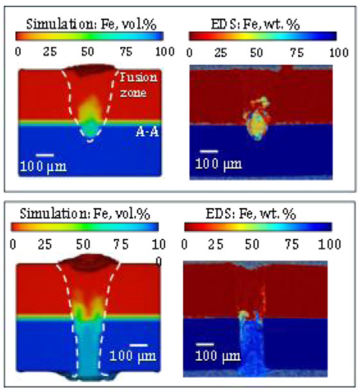

Fig. 23. Example of multi-physical CFD simulation correlated to EDS map to study the material mixing evolution in welding of Cu to hilumin [34].

A Scheil model was also applied to predict phase distribution based on thermo-solute conditions. At the micro-scale, recent advances in computational materials science enable coupling multi-physics and multi-scale models to simulate 3D grain evolution. These approaches combine finite element methods (FEM) with cellular automata (CA) to model dendritic growth. More advanced methods use phase-field (PF) models to predict solidification behavior in multi-component alloys [134]. Mesh design is a critical aspect of these simulations, affecting both accuracy and computational cost. Fine meshes are required near the laser source to capture steep gradients, typically with at least 10 elements across the beam diameter, while adaptive meshing is applied elsewhere. However, these models often involve more than one million elements and require significant computation time, limiting industrial applicability. To address these limitations, Physics-Informed Neural Networks (PINNs) are emerging as a promising alternative. By embedding physical laws into data-driven models, they improve predictive capability with limited data and enable applications in monitoring and model predictive control [212].

6. Outlook and future trends

This section examines the current limitations and future directions of LBM in the context of powertrain fabrication. It first identifies the key gaps that hinder the scalable and robust industrial deployment of laser technologies in EV production. Building on this analysis, the outlook is then discussed for liquid-electrolyte lithium-ion batteries, electric drives, fuel cells and solid-state batteries, highlighting domain-specific manufacturing challenges and opportunities. Finally, the section synthesizes these insights to identify the meaningful step changes required at the manufacturing system level to fully exploit laser-based technologies.

6.1. Gaps in laser-based manufacturing for EV production

Despite the rapid adoption of laser-based processes in EV manufacturing, significant gaps remain between the current state of the art and the requirements of robust, scalable and sustainable industrial production. These gaps span methodological, technological and system-level dimensions and can be summarized as follows. A **first** critical gap concerns the lack of standardised benchmarks and harmonised reporting protocols. Key process parameters (such as spot size, beam shape, scanning strategy and shielding conditions) are often inconsistently reported. This limits comparability, reduces reproducibility and complicates industrial scale-up. A **second** gap is the mismatch between laboratory validation and industrial requirements. Many processes demonstrate excellent performance under controlled conditions but remain limited to low throughput. As a result, their applicability to high-volume manufacturing is uncertain. While laser cutting and welding are already industrially mature, processes such as structuring and surface functionalization are still constrained by scalability. **Material-related challenges represent another limitation**. Materials such as copper and aluminum exhibit high reflectivity and thermal conductivity, leading to unstable process windows. This often results in defects such as porosity, spatter and brittle intermetallic phases, which can compromise both mechanical and electrical performance. **Process robustness is also a key issue**. Variability in geometry, material properties and upstream processes affects weld quality. Current monitoring solutions are often limited to post-process inspection or partial diagnostics. Fully integrated, real-time closed-loop control systems are still lacking. **Emerging technologies** (such as optical coherence tomography, photodiode-based sensing with machine learning, and acoustic monitoring) offer promising solutions. However, their industrial adoption is limited by integration complexity, cost, and data interpretation challenges. Similarly, advanced modelling approaches, including multi-physics simulations and physics-informed neural networks, show strong potential but are still constrained by computational cost and latency. Overall, the main challenge is no longer the feasibility of individual laser processes, but their integration into coherent, scalable and intelligent manufacturing systems. Addressing these gaps is essential to fully exploit LBM and supports the outlooks for LIBs, SSBs, fuel cells and electric drives discussed in the following sections.

6.2. Outlook for laser processing of lithium-ion batteries

LIBs are expected to remain the dominant energy storage technology for EVs over the next decade. From a manufacturing perspective, the most impactful innovations will arise from improvements in production efficiency, quality assurance, and system integration, rather than from major changes in cell chemistry. **In electrode manufacturing**, laser drying, structuring, and cutting play a key role in improving performance, productivity, and process stability. Laser cutting has reached full industrial maturity and is widely adopted in production. Laser drying has also progressed toward industrial implementation, with commercial laser-drying systems already available, typically integrated alongside conventional oven-based drying lines. In contrast, laser structuring is still mainly limited to laboratory-scale applications, as current laser and optical systems do not yet enable the high throughput required for industrial production, also due to the high cost of the equipment needed to achieve elevated productivity levels. A key step change lies in the integration of multiple laser-based operations into unified manufacturing stages:

- **Integration of laser processes in unified platforms**
  - combining cutting, drying, selective structuring and in-line inspection within a single roll-to-roll platform [90];
  - enabling more compact, efficient, and controllable production systems.

Achieving this integration requires technological advances:

- **Enabling technologies for process integration**
  - development of high-power ps and fs laser sources with reduced costs, enabling their adoption in industrial production without leading to unacceptable cost increases for electrode structuring.
  - improved beam delivery, advanced scanning strategies and optimized thermal management;
  - real-time diagnostics and deeper understanding of the relationship between laser-induced microstructural modifications and long-term performance and ageing.

In **cell and module assembly**, laser welding is already industrially established. However, future requirements will be increasingly driven by material variability, dissimilar metal combinations, and tighter tolerances. Addressing these challenges requires:

- **Advanced control strategies for welding processes**
  - adaptive energy delivery and manufacturing-driven beam shaping;
  - closed-loop control systems capable of compensating for process variability in real time.

Within this framework, LBM must evolve from a deterministic tool into a self-adaptive manufacturing paradigm:

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- **Transition toward self-adaptive manufacturing systems**

  - actively managing variability rather than simply tolerating it;
  - integrating sensing, modelling, and control within a unified production architecture.

Sustainability adds a further dimension to future LIB manufacturing. Laser technologies offer intrinsic advantages such as material selectivity, process localization, and reconfigurability. These characteristics enable new circular production approaches:

- **Enabling circular manufacturing strategies**

  - selective electrode reworking and repair;
  - non-contact disassembly and high-purity material recovery.

Although still largely unexplored, these approaches represent a significant opportunity to transition toward lifecycle-oriented battery manufacturing systems.

6.3. Outlook for laser processing of electric drives

Electric drives based on hairpin stators are expected to remain the reference solution for high-volume EV production. This places stringent requirements on manufacturing robustness, defect tolerance and zero-failure operation. Laser stripping and laser welding of hairpins are already established at industrial scale. However, future progress will depend mainly on system-level optimization rather than further refinement of individual processes. A key step change is the need to close the loop between upstream variability and downstream laser operations. Material deviations, geometric tolerances and fixture wear directly affect weld quality. To address this, laser systems must integrate in-process sensing, real-time adjustment and predictive modelling to ensure stable performance under non-ideal conditions. Beam shaping and dynamic scanning offer strong potential to improve joint quality and reduce spatter. However, their current use remains largely empirical. A major research direction is the development of physics-informed beam shaping. In this approach, energy delivery is explicitly linked to joint geometry, thermal history and functional requirements such as electrical resistance and fatigue life [67]. Process stability can be further improved through precise gap control and real-time monitoring. Techniques such as coaxial cameras [80], photodiodes [159], acoustic sensors and optical coherence tomography enable both pre-weld positioning and in-process quality assessment [175]. Beyond hairpin welding, LBM is expected to expand to additional operations. These include laser cutting of electrical steels for improved geometric flexibility and additive manufacturing of stator components and sub-assemblies in steel and copper [157]. In these emerging applications, beam shaping enables control of microstructure and electromagnetic properties. This highlights the need for tighter integration between motor design, materials science, and laser process engineering.

6.4. Outlook for laser processing of solid-state batteries

Over the past decade, LIBs have undergone significant technological advancements and process optimization. Nonetheless, their development is approaching a performance plateau, constrained by limitations in maximum achievable energy and power densities, as well as safety concerns associated with the flammable liquid electrolyte [81]. Consequently, the battery industry is expected to transition toward next-generation technologies. Among these, solid-state batteries (SSBs) offer promising improvements in energy density, chemical stability and safety. These advantages are primarily enabled using solid electrolytes (SE). Lithium-metal SSBs are considered one of the most promising candidates, as they combine high energy density with improved safety. This discussion therefore focuses on lithium-metal SSBs, while other chemistries such as sodium- and potassium-based systems remain at an early stage of development [284]. When considering SSBs, the following key aspects should be highlighted before discussing the details in the next sections:

- **Interface engineering as a central challenge**

  - Battery performance is strongly affected by interfacial resistance, void formation and dendrite growth.
  - These phenomena depend on local microstructure, surface chemistry and contact quality.

- **Structural similarities and differences with LIBs**

  - SSBs share the same main components: anode, cathode and electrolyte.
  - However, they differ significantly in material selection and, more importantly, in interface requirements.

- **Implications for performance and reliability**

  - Interfaces play a dominant role in SSBs.
  - Their control is critical for achieving stable and high-performance battery operation.

Overall, this highlights that controlling interfaces is the key enabler for achieving high performance and reliability in lithium-metal SSBs. To address these challenges, LBM offers unique capabilities for precise and localized material processing. Laser technologies enable controlled surface modification, selective material removal and high-resolution interface engineering, which are critical for SSB performance. The following sections examine how LBM can be applied to the key components of SSBs, focusing on anodes, cathodes and solid electrolytes.

6.4.1. Laser based manufacturing applications for solid-state batteries anodes

Lithium metal and silicon are the preferred anode materials for SSBs. Lithium metal offers the highest energy density but poses manufacturing challenges due to its high reactivity and interface sensitivity. Conventional die-cutting is unsuitable, as adhesion and toughness lead to rapid tool wear. Laser cutting provides a flexible, non-contact alternative. Early studies demonstrated effective lithium ablation using ns pulsed fiber lasers, with peak powers up to 13 kW and cutting speeds up to 150 mm/s [104]. To achieve industrially viable throughput, high-repetition PW or CW laser sources are required. In addition, shorter pulse durations (ps or sub-ps) are preferred to reduce defects such as recast layers. Recent work using Yb fiber ns lasers has further improved process understanding. These studies linked process parameters to cutting width and defect formation using response surface methodology (RSM) [117] and ANOVA methods [19]. They also addressed oxidation effects on lithium metal surfaces [165]. Overall, laser processing is emerging as the most promising solution for precise anode shaping. Ongoing research focuses on improving process stability and quality. Notably, laser etching of the copper current collector before lithium deposition has been shown to increase battery cycle life by up to 200% [236].

6.4.2. Laser based manufacturing applications for solid-state batteries cathodes

Dominant cathode active materials include NMC for superior electrochemical performance, nickel cobalt aluminum oxide (NCA) for high energy density LFP for cost-effective applications [185]. From a materials perspective, no substantial differences exist between cathodes used in SSBs and those employed in LIBs; consequently, the technical state of the art for cathode materials remains essentially the same as that described in Section 3.

6.4.3. Laser based manufacturing applications for solid-state batteries separators

In SSBs the solid electrolyte (SE) is a key manufacturing component [185]. While several electrode fabrication approaches developed for LIBs can be partially transferred to SSBs production, the fabrication and integration of thin, dense solid electrolyte separators remain a key manufacturing bottleneck. LBM techniques have attracted strong interest in this area because they offer non-contact and highly controllable solutions for structuring, thinning and interfacing solid electrolytes. This makes LBM particularly suitable for addressing scalability challenges in SSB production. In particular, laser-based cleaning, texturing and localized modification enable precise engineering of electrode–electrolyte interfaces improving contact quality and allowing better control of ion transport [81]. Laser technologies are being developed to resolve interfacial stability issues in SSBs [183]. SSB cells include several critical interfaces, each introducing specific manufacturing challenges. These include the lithium anode/solid electrolyte interface, interfaces within the solid electrolyte, composite cathodes and electrode/current collector contacts. From a manufacturing perspective, the main objectives are to improve lithium wettability, reduce porosity, shorten ionic and electronic transport paths and suppress void and dendrite formation. In this context, laser-based treatments have shown strong potential. They are particularly effective at improving the lithium anode/solid electrolyte interface and enhancing the performance of composite cathodes. At the anode interface, reactions with atmospheric moisture and CO_2 lead to the formation of Li_2CO_3 surface layers, which degrade ion transport and promote void and dendrite growth [183]. Nanosecond PW laser cleaning has been shown to effectively remove these layers, reducing interfacial resistance from 2497.7 to 76.4 $\Omega \cdot cm^2$ [31], while laser surface structuring further enhances lithium-ion transport and mitigates short-circuit formation. In [116] surface contaminants were effectively removed from lithium metal substrates using ps PW laser irradiation, resulting in up to a 44% reduction in interfacial resistance. Additionally, ultrafast pulsed lasers have been successfully used to structure solid electrolytes. This approach reduces ionic and electronic transport path lengths within cathode particles, improving overall performance. In [119] a preliminary comparative study between ns and ps laser pulses was conducted for the structuring and cutting of LATP□ electrolyte. Both pulse durations yielded high surface quality; however, it was determined that ps pulses enhanced volume and depth ablation efficiency relative to ns pulses. Nonetheless, the ablation efficiency diminished when MHz burst modes were applied within the ps regime. In parallel, increasing SSB energy density requires solid electrolyte and composite cathode layers below ~25 µm, a regime in which ceramic brittleness limits mechanical processing. Under these conditions, laser-based cutting and structuring emerge as the most suitable manufacturing solutions for thin solid electrolyte layers [120]. In [121] three-dimensional microstructured patterns were laser-ablated into oxide solid electrolyte layers. These structures were then infiltrated with cathode slurries containing active materials and ion-conductive polymer electrolytes. This approach enabled the fabrication of hybrid composite cathodes with improved electrode–electrolyte interface properties. In [118] NIR, green and ultraviolet ps laser pulses were employed to fabricate cavities and trenches in solid electrolyte lithium aluminum germanium titanium phosphate. Optimal fluence levels and ablation efficiencies were established for all three wavelengths. Material defects such as cracking and chipping were observed at a wavelength of λ = 1064 nm, whereas superior surface quality with surface roughness (Sa) below 1 μm was achieved at λ = 532 nm and λ = 355 nm, under optimal fluence conditions. However, manufacturing throughput remains a critical limitation [167]. When using fs lasers to achieve high-quality features, structuring speeds are typically around 0.5 m/s [30]. Using ps lasers, speeds can increase up to about 1.3 m/s, but often at the expense of microstructural defects [118]. Finally, it is worth mentioning preliminary studies in the fields of selective laser sintering of SE and cathodes particles, of SE separators and of composite cathodes. They are promising in the future to solve some issues, but they are low, there are problems related to the ablation during sintering and to the degradation of conductive auxiliaries [222].

6.4.4. Summary of laser-based manufacturing in solid-state batteries

To synthesize, the key aspects discussed in the previous sections can be summarized as follows:

- Transition to SSBs: LIBs are approaching performance limits, shifting focus to SSBs, where interface engineering between electrodes and solid electrolytes is critical for performance and stability.
- Anode processing: Laser cutting enables precise shaping of lithium metal, overcoming limitations of mechanical methods. Surface treatments further improve interface quality and battery lifetime.
- Cathode processing: NMC, NCA and LFP remain the dominant options, with no major differences between SSBs and LIBs processes.
- Separators (SE): Laser cleaning, structuring and texturing enhance ion transport and interface stability. Ultrafast lasers are effective for processing thin and brittle ceramic layers, although throughput remains a limitation.
- Manufacturing limitations and opportunities: while laser-based techniques offer high precision and control, scalability is still constrained by process speed and system complexity.

6.4.5. Laser based manufacturing applications for solid-state batteries at industrial scale level

At the industrial scale, SSB manufacturing further highlights the importance of precise energy control. Processing of SE such as cutting, structuring and thinning requires strict thermal management to avoid cracking, delamination and phase degradation. Ultrafast and short-pulsed lasers offer promising solutions for these applications. However, their industrial adoption is still limited by low throughput and system complexity. To overcome these limitations, the same step changes identified for LIBs are required. These include parallelization, multi-beam architectures and the integration of multiple functions (e.g., structuring and inspection) within unified manufacturing systems. Assembly and stacking operations introduce additional challenges. Stack pressure, layer alignment and material variability strongly influence performance and yield. In this context, LBM systems with in-process sensing and real-time control can enable adaptive adjustments, reducing sensitivity to upstream variability. Although SSBs offer the potential to outperform LIBs, scalability remains a key challenge. Several pilot production lines have been demonstrated for different types of solid electrolytes, including sulfide [191], oxide [189] and hybrid systems [10], as well as lithium-metal SSBs [114]. Despite these advances, SSB technology has not yet reached economic viability. Bridging the gap between laboratory research and industrial production requires the development of prototype and pilot-scale manufacturing lines [124]. To move beyond laboratory demonstrations, laser-based processes must be integrated into scalable manufacturing chains. This requires a shift from isolated laser operations toward fully integrated manufacturing architectures, with a strong focus on laser-enabled interface control. As summarized in Table 9, the transition from LIBs to SSBs shifts LBM from throughput-driven processes toward interface and precision-critical operations and LBM

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Table 9
Key LBM processes: transition from LIBs to SSBs.

Laser-based process	*Role in LIB manufacturing*	*Role in SSB manufacturing*	*Key transition (LIB → SSB)*	*Manufacturing maturity*
Laser drying	Solvent removal in wet-coated electrodes	Marginal	From bulk drying to limited, localized functions	LIB: pre-industrial/ industrial SSB: emerging
Laser structuring	Enhances ion transport in thick electrodes	Controls electrode–SE interfaces	From bulk transport to interface engineering	LIB: lab/pilot SSB: lab
Laser cutting (electrodes)	High-speed cutting of coated foils	Precision cutting of SE layers and Li metal	Tighter thermal control and lower damage tolerance	LIB: industrial SSB: pre-industrial
Laser cutting (current collectors)	Industrial shaping of Cu and Al foils	Similar, but often integrated with interface engineering	SSB often integrates CC processing with SE constraints	LIB: industrial SSB: emerging
Laser cleaning	Surface preparation before joining	Critical for Li–SE interface stability	From optional to enabling process	LIB: near-industrial SSB: pilot
Laser welding	Tabs, busbars, CC joining	Limited, stack-constrained joining	From high-speed joining to constrained operations	LIB: industrial SSB: early research
Ultrashort-pulse lasers	Quality-driven structuring/cutting	Enabling for brittle ceramics and Li metal	From niche to essential technology	LIB: niche SSB: enabling

is expected to remain a key enabling platform due to its capabilities in precision processing and interface engineering.

6.5. Outlook for laser processing of fuel cells

From a manufacturing perspective, laser-based technologies are expected to play a central role in fuel cell production. This is due to the stringent requirements associated with thin metallic components, complex geometries and multifunctional surfaces [4]. One of the main challenges concerns bipolar plates. These components account for a large share of both system cost and mass. Laser cutting and welding are already widely used for shaping and joining thin metallic plates. They enable high geometric flexibility and precise sealing of complex flow-field designs [235]. However, future applications will require tighter control of dimensional accuracy, lower thermal distortion and improved corrosion resistance in welded regions. Achieving these targets will require advances in beam shaping, energy modulation and process control, moving toward more physics-informed approaches. Surface functionalization is another key area for improvement [45]. Laser texturing and micro-structuring can tailor surface properties such as roughness, wettability and contact resistance, directly affecting water management, reactant distribution, and conductivity. Industrial adoption requires improvements in throughput, uniformity, and repeatability, supported by parallel processing and in-line inspection. At system level, fuel cell manufacturing shares challenges with batteries and drives, including scalability, quality assurance and real-time monitoring. Future progress in LBM will rely more on integration and optimization of existing technologies than on new processes, enabling cost-effective and reliable fuel cell production.

6.6. Meaningful step changes in laser-based manufacturing for electric mobility

In the context of LIBs, SSBs, electric drives and fuel cells current laser sources already meet the requirements in terms of power, beam quality, flexibility and wavelength. This applies to both CW and PW operation. Therefore, future innovation is expected to depend less on the laser itself and more on how it is integrated into manufacturing systems [42]. In this perspective, a set of key step changes can be identified to fully exploit the potential of LBM in electric mobility manufacturing:

- A **first** key step change is the shift from process optimization to manufacturing architecture design [249]. So far, LBM has often been added to existing production lines designed for mechanical or chemical processes. This limits its full potential. Future systems should instead be designed around laser capabilities, such as localized energy input, geometric flexibility, and digital control. This applies across LIBs, SSBs, electric drives, and fuel cells.
- A **second** step change concerns scalability. Many advanced laser processes are still limited by low throughput. Increasing laser power alone is not sufficient, as it raises cost and complexity [186]. Instead, scalability must be addressed at system level. This includes multi-beam architectures, parallel processing and optimized scanning strategies.
- A **third** step change is the move from empirical parameter tuning to manufacturing-driven energy coordination [34]. Today, beam shaping and modulation are mainly used to stabilize processes. In the future, energy delivery should be designed as a function of geometry, thermal history, and performance requirements. This is particularly important for dissimilar material welding, interface engineering in SSBs, and surface functionalization in fuel cells.
- A **fourth** step change is the transition toward self-adaptive, defect-tolerant systems. High-volume production requires robustness against material variability and process drift. Traditional approaches based on fixed parameters and post-process inspection are no longer sufficient. Future systems must integrate in-process sensing, modelling, and data-driven control to manage variability in real time.
- A **fifth** step change concerns sustainability. Lasers enable selective reworking, repair, and non-contact disassembly of components. These capabilities are important for battery remanufacturing, electric drive refurbishment, and fuel cell recovery, supporting circular production models.
- **Finally**, a cross-cutting step change is needed in how LBM is developed and validated. The lack of standardized benchmarks and shared datasets limits industrial adoption.

Table 10
The main challenges and the step changes required in laser-based manufacturing for key electric mobility applications.

Product	Key laser applications	Main manufacturing challenges	State of the art → required step changes
LIBS	Electrode cutting and drying; tab, cell and module welding; electrode structuring; cleaning	Throughput, Cu/Al variability, roll-to-roll integration	Cutting, cleaning and welding industrial; drying and structuring at pilot level → multi-beam systems, closed-loop control
SSBS – ANODES	Laser cutting of Li-metal/Si; surface cleaning and texturing; collector etching	Li reactivity, oxidation, interface stability	Lab-scale ns/ps lasers → ultrafast/high-rep sources, inline integration, defect suppression
SSBS – SE	Laser cutting/structuring; etching	Ceramic brittleness, thermal control, throughput	Demonstrations with ns/ps/fs lasers → parallelization, multi-beam systems, integrated structuring & inspection
SSBS – System level	Integrated laser cells; laser-assisted stacking and assembly	Scalability, yield, system complexity	Pilot lines demonstrated → adaptive manufacturing, industrial validation, scalable chains
Electric drives	Hairpin stripping and welding; steel cutting; AM stator parts	Fixture wear, gap variability, zero-failure	Industrial maturity → physics-informed beam shaping, real-time gap control, self-adaptive systems
Fuel cells	Bipolar plate cutting, welding, surface texturing	Accuracy, distortion, corrosion, repeatability	Cutting/welding industrial; texturing at lab level → beam shaping, parallel processing, inline inspection
Cross-cutting	Beam shaping, dynamic scanning, OCT, photodiodes	Lack of benchmarks, limited transfer	Need for standardized metrics, closed-loop control, system-level validation
Circularity	Laser repair, reworking, disassembly	Integration into production systems	Largely unexplored → lifecycle-oriented laser manufacturing

Future work must focus on validation under realistic production conditions, with emphasis on reproducibility, scalability, and system integration. An overview of LBM applications and challenges is provided in Table 10.

7. Summary

Laser-based manufacturing has become a key enabling technology for electric mobility, supporting the production of energy storage systems and electric drives that define modern EVs. This keynote has reviewed the state of the art of LBM across batteries, fuel cells and electric drives, showing how laser processes are increasingly embedded in industrial manufacturing chains. The analysis confirms that lasers are not only versatile production tools, but also technologies that enable new component designs, tighter tolerances and higher levels of automation. Several laser-based processes, including cutting of CCs and electrodes, welding of battery interconnections and hairpin welding for electric drives, can be considered industrially mature. These processes are already implemented in high-volume manufacturing and benefit from the intrinsic advantages of lasers, such as non-contact operation, high precision, repeatability and geometric flexibility. At the same time, other processes such as electrode structuring, laser drying and advanced surface functionalization remain at lower technological readiness levels. Although their potential benefits in terms of performance, sustainability and design freedom are well documented at laboratory scale, their widespread industrial adoption is still constrained by limited throughput, higher costs and sensitivity to process variations under realistic manufacturing conditions. The review highlights that progress in LBM for electric mobility is increasingly driven by system-level considerations rather than by the optimization of individual processes in isolation. Advances in laser sources, beam shaping technologies and scanning optics have significantly expanded the available process windows and enabled higher productivity and improved quality. However, these advances have also increased the complexity of process parameter selection, equipment configuration and line integration. This complexity reinforces the need for systematic methodologies for process design, benchmarking and scale-up, as well as for standardized reporting of experimental conditions to improve comparability, reproducibility and technology transfer between research and industrial environments. Process monitoring and control are identified as critical enablers for robust and reliable LBM in EV manufacturing. While sensing technologies such as photodiodes, optical coherence tomography, vision systems and acoustic monitoring have demonstrated strong potential for in-process quality assessment, robust real-time detection of subsurface defects and reliable closed-loop control remain open challenges. Data-driven approaches, including machine learning and physics-informed models, offer promising pathways toward predictive process control and reduced scrap rates. Nevertheless, their industrial deployment is still limited by the availability of large, representative datasets, the generalization of models across materials and geometries, and the computational constraints associated with real-time operation. Looking forward, the evolution of energy storage technologies, particularly the transition toward solid-state batteries, is expected to introduce new manufacturing challenges that are well aligned with the strengths of laser-based processes. Precise material removal, interface engineering, and processing of brittle or highly reactive materials are areas where LBM is likely to play an increasingly important role, provided that scalability and economic viability can be demonstrated. In parallel, electric drive manufacturing will continue to demand higher process stability, tighter defect tolerances and adaptive control strategies, further reinforcing the importance of advanced laser systems integrated with monitoring and control solutions. In conclusion, LBM already plays a central role in the production of EV powertrains and is expected to gain further importance as materials, component architectures, and performance targets continue to evolve. Continued progress will depend on coordinated advances in laser hardware, process understanding, modelling, monitoring and control, with a strong emphasis on industrial validation and scalability. Addressing these challenges will be essential to ensure that LBM can reliably support the next generation of electric mobility systems and contribute to the long-term competitiveness and sustainability of the manufacturing sector.

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Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this manuscript, the author(s) used ChatGPT (version 5.2) to improve the clarity, readability, and overall quality of the English language, particularly in response to reviewers' requests to enhance the clarity and exposition of the manuscript. After using this tool, the author(s) carefully reviewed and edited the content as necessary and take full responsibility for the content of the published article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

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