



Review article

## A review of research needs in nondestructive evaluation for quality verification in electric vehicle lithium-ion battery cell manufacturing



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### HIGHLIGHTS

- Rapid disruptive shift from internal combustion engine to battery electric vehicles.
- Nondestructive evaluation (NDE) necessary for first-time quality EV batteries.
- NDE for Li-ion cell manufacturing difficult due to many simultaneous constraints.
- NDE technologies must drastically evolve to keep pace with cell manufacturing.
- Research gaps are identified and presented for NDE in EV battery manufacturing.

### ARTICLE INFO

**Keywords:**  
Lithium-ion  
Electric vehicles  
Battery cells  
Nondestructive evaluation  
Manufacturing  
Quality verification  
Inline inspection

### ABSTRACT

The world is rapidly shifting from internal combustion engine vehicles to battery electric vehicles (EV). EV battery manufacturing requires nondestructive evaluation (NDE) solutions for quality verification that can operate under a unique set of constraints, including extremely fast cycle times, small geometric scales, and conductive materials. Individually, the demands imposed by many of these constraints can be met with existing technologies. As a collective, however, they prove challenging to conventional NDE technologies. *It is therefore imperative that NDE methods and technologies drastically evolve to keep pace with this disruptive paradigm shift.* The goal of this paper is to provide a summary of the current research needs for NDE in EV battery cell manufacturing.

### 1. Introduction

The world is rapidly shifting from internal combustion engine vehicles to battery electric vehicles (EV). Detroit's "Big Three"<sup>1</sup> automakers predict that EVs will make up 40%–50% of the annual vehicle sales volume by 2030 [1–3]. US passenger EV sales alone are projected to increase from 3.1 M in 2020 to 14 M by 2025 (16% of global 2025 predictions) [4]. This disruptive technological shift foreshadows the need to implement quality verification systems to maximize first-time quality in EV battery manufacturing. Nondestructive evaluation (NDE) methods and technologies must adapt to this new paradigm. The goal of this paper is to provide a summary of the current research needs for NDE

in EV battery manufacturing.

Several recent high-profile cases of defective battery cells have demonstrated the importance of adopting NDE manufacturing solutions [5–11]. These examples range from consumer electronics to commercial mobility to home energy storage applications. For all cases, manufacturing defects increased the risk of a thermal runaway event. As cell energy densities trend higher, the severity of thermal runaway events will also increase [12].

NDE advancements have been traditionally dominated by non-automotive domains such as aerospace, pipeline, and structural applications. EV battery manufacturing requires new NDE solutions that can operate under substantially different constraints, including extremely

**Abbreviations:** NDE, Nondestructive Evaluation; EV, Electric Vehicle; CT, Computed Tomography; OCV, Open Circuit Voltage; SEI, Solid Electrolyte Interphase; EOL, End-of-Line; SEM, Scanning Electron Microscope; EDS, Energy Dispersive X-ray Spectroscopy.

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<sup>1</sup> The "Big Three" colloquially refers to the three US automakers historically in the Detroit area: General Motors, Ford, and Stellantis (formerly Chrysler).

fast cycle times, different materials, and much smaller geometric scales [13]. Individually, the demands imposed by many of these constraints can be met with existing NDE technologies. Automotive Li-ion battery cell manufacturing is exceptionally difficult in that all these constraints are simultaneously present. *It is therefore imperative that NDE methods and technologies drastically evolve to keep pace with this disruptive paradigm shift.*

This paper's scope will be limited to lithium-ion (Li-ion) pouch battery cell manufacturing; however, many of the subsequently described manufacturing techniques are not limited to pouch cells and can be applied to can cells. It is organized to sequentially follow the battery cell manufacturing processes. Neither a background in EV batteries nor the manufacturing processes is assumed; therefore, high-level descriptions will be provided. Sections will be generally organized into three parts: 1. "Process," which will contain a brief description of the manufacturing process; 2. "State-of-the-Art Nondestructive Evaluation Techniques," which will describe NDE techniques currently applicable to inspecting for conformance to specifications and possible defects; and 3. "Opportunities in Nondestructive Evaluation," which will discuss NDE research gaps. The authors intend for this paper to be read as a reference and to be used as a guide for any researcher wishing to enter this domain. Accordingly, it will only describe the battery manufacturing processes and NDE techniques with a level of detail sufficient to provide the reader with a "starting point." For the purposes of this paper, conformance will refer to adherence to manufacturing and product requirements and defects will refer to any characteristic that yields a part that does not meet specifications and may result in non-conforming performance.

While specific emphasis will be placed on Li-ion pouch cells, the battery cell field is rapidly evolving. The final section will therefore contain a brief discussion on future advanced manufacturing processes, electrochemistries, and their potential impact on NDE technology needs.

## 2. Lithium-ion battery cell manufacturing

A Li-ion battery cell is a multi-layered structure comprised of anodes, cathodes, and separator layers. See Fig. 1. The cathodes, positive electrodes, consist of aluminum foil current collectors coated with a lithium oxide powder. The anodes, negative electrodes, consist of graphite coated copper foil current collectors. Anodes and cathodes are separated by an electrically insulating, porous membrane called the separator which allows Li ion transport via a liquid electrolyte while preventing physical contact between the electrodes. This combination of layers is termed the electrode-stack. It is assembled so that a positive and negative external cell tab (i.e., an aluminum or copper lead) is welded to notched and uncoated portions of the aluminum or copper electrode foils. The electrode-stack is encased in an insulating pouch, with the

battery tabs protruding, and filled with an electrolyte liquid which fills the coating pores and any remaining space to enable Li-ion movement.

During charging, the cathode releases lithium ions, which travel via the electrolyte and are stored in the anode graphene layers. Electrons flow from the cathode to the anode via the external electrical circuit. Discharging is the reverse, with electrons flowing from the anode to the cathode via an external circuit. The lithium ions are stored in the lithium oxide layers of the cathode for a fully discharged cell.

Fig. 2 contains a schematic of a typical Li-ion pouch cell manufacturing process. As noted, the focus here will be on pouch cells. Whether the Li-ion cell is pouch, prismatic, or cylindrical, cell manufacturing fabrication comprises three major steps: 1. Electrode manufacturing, 2. Cell assembly, and 3. Formation. Once a cell is full assembled, it reaches End-of-Line, where it is aesthetically finished, tested, and prepared for shipping. Some materials will be considered as "incoming" (e.g., purchased from a supplier) and their manufacturing details will be omitted. These include active materials, separator, pouch material, etc. The remainder of this report will detail the processes in Fig. 2 and their corresponding inspection needs. Though all attempts have been made to maintain consistent jargon, certain contexts conventionally use different language for the same idea; therefore, a Glossary of Terms is provided in Appendix A in Table 2 to aid the reader.

### 2.1. Electrode manufacturing

Electrode manufacturing is the first major cell manufacturing step which begins with slurry mixing and concludes with a completed set of anode and cathode electrodes. After mixing the slurries, the processes within the electrode manufacturing step are roll-to-roll. This section will describe the processes involved in electrode manufacturing as outlined in the blue region of Fig. 2, beginning with "Mixing" and ending at "Slitting and Notching." Vacuum drying will not have a dedicated section and will only briefly be mentioned in "Slitting and Notching."

Defects must be caught early with inline nondestructive inspection technologies to minimize scrap. A majority of the electrode manufacturing processes are roll-to-roll of very thin metal foils. NDE technologies must therefore be non-contact to avoid contamination or foil damage, quick to accommodate roll-to-roll speeds in excess of 50 m/min [14], and applicable to thin (10s–100s of  $\mu\text{m}$ ) electrodes with a highly conducting metal core coated on both sides with a moderately-conductive coating. The simultaneous presence of these constraints poses a challenge for most existing NDE technologies.

As will be shown in the following sections, the biggest NDE research needs involve inline inspection and characterization of porosity, thickness, thickness uniformity, surface roughness, and internal/surface defects for these thin, quick moving, coated electrodes. The following sections will detail specific conformance requirements as well as the

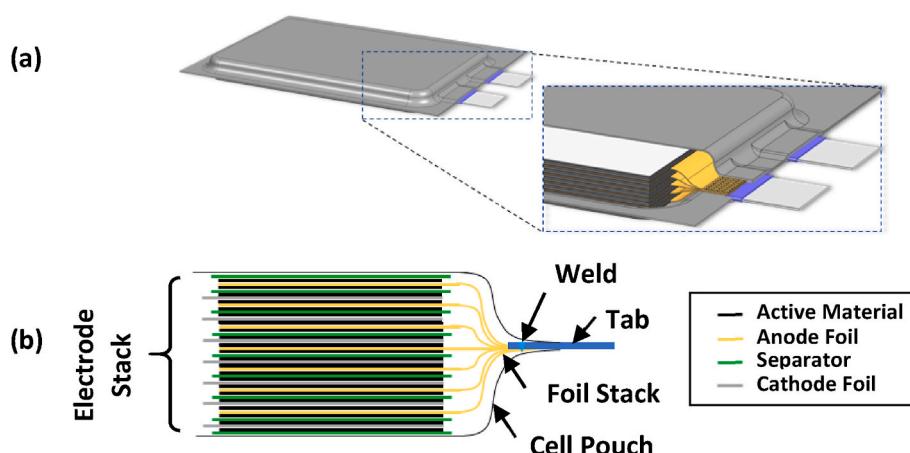


Fig. 1. A (a) 3D and (b) cross-section schematic of a Li-ion pouch cell.

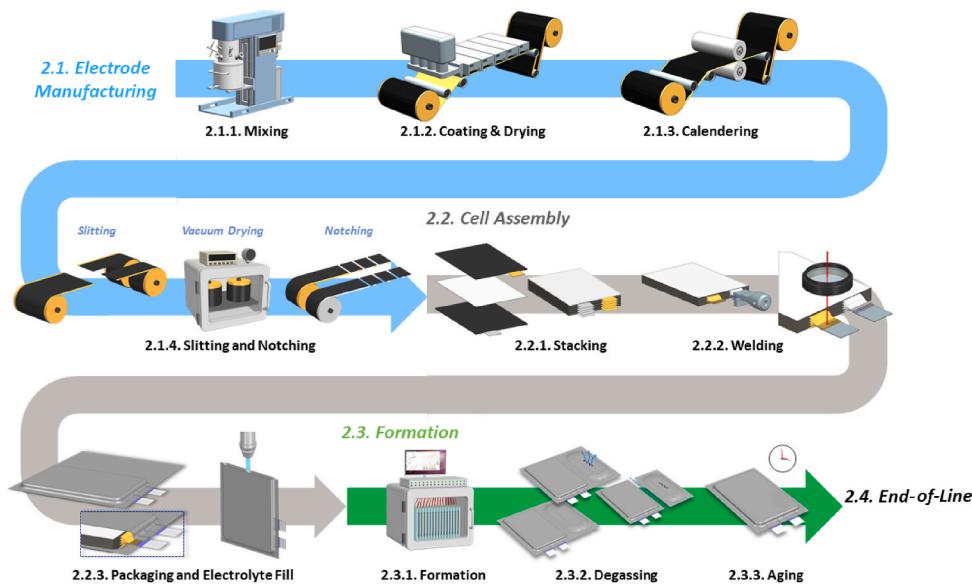


Fig. 2. A typical Li-ion pouch battery cell manufacturing process.

potential defects that inspection technologies must evaluate.

#### 2.1.1. Mixing

**Process:** The slurry mixing process is the homogenizing step, where the raw particulate materials are dispersed in the liquid solvent [15]. Slurries are suspension liquids which coat the aluminum and copper current collectors to create the cathode and anode, respectively. Slurries consist of active material particles, conductive additives, polymer binder, and a solvent medium. The active material particles store and release lithium ions during charging and discharging. Lithium oxides serve as the cathode active material. Common lithium oxides include lithium manganese oxide ( $\text{LiMn}_2\text{O}_4$  or LMO) [16], lithium cobalt oxide ( $\text{LiCoO}_2$  or LCO) [15], lithium iron phosphate ( $\text{LiFePO}_4$  or LFP), lithium iron manganese phosphate ( $\text{LiMn}_x\text{Fe}_{1-x}\text{PO}_4$  or LFMP), lithium nickel cobalt manganese oxides ( $\text{LiNi}_{1-x-y}\text{Co}_x\text{Mn}_y\text{O}_2$  or NMC or NCM) [17], or lithium nickel cobalt manganese aluminum oxide ( $\text{LiNi}_{0.89}\text{Co}_{0.05}\text{Mn}_{0.05}\text{Al}_{0.01}\text{O}_2$ ) [18]. A common anode active material is graphite [19]. Conductive additives, such as carbon black, enable electron transport throughout the electrode. A polymer binder, such as polyvinylidene fluoride (PVDF) for cathodes or carboxymethyl cellulose (CMC) for anodes, binds the conductive additive particles with the active material and adheres them to the foil. A solvent material, such as N-methyl pyrrolidone (NMP) for PVDF or water for CMC, is necessary to dissolve the binder and obtain a uniform slurry with the desired rheological properties [16,19–23]. There is a large body of research [15–17, 19–21,22,24,26,27] surrounding the science of slurry preparation, including considerations of mixing sequence, raw materials, equipment, shear forces, filter materials and systems, mixing temperature, etc.

For large-scale industrial applications, a common mixer is the planetary mixer [20]. Once mixed, the tank containing the fully homogenized slurry is transported to the coating line to be deposited on the current collectors.

**State-of-the-Art Nondestructive Evaluation:** Slurry conformance inspection focuses on rheological and particle distribution/dispersion property monitoring. All incoming material must conform to specified properties (particle size and distribution, material type, etc.) and be free of contaminants. The quality of a slurry is ultimately determined by its uniformity and stability. A uniform and stable slurry is free of large-particle sedimentation, small particle agglomeration, and has the targeted solids content [26]. An ideal slurry will have a low enough viscosity under shear to enable mixing, yet high enough viscosity in the absence of shear to maintain homogeneity [28].

The rheological and mechanical properties of slurries are also important from a manufacturability perspective. The presence of agglomerated materials will yield a non-conforming electrode coating [15,29,30]. Contamination due to equipment-wear or malfunction (e.g., mixer blades scraping the bucket) can introduce unwanted metal particulates to the slurry. Beyond the mixing process, equipment-wear can unintentionally introduce iron particles to the slurry anywhere on the manufacturing line. Though uncommon, debris could also be introduced to the slurry if the battery cell fabrication lab spaces are not kept clean or proper clean-room protocols are not enforced.

Though in-situ rheology measurements exist [31], in practice battery slurry rheological testing is performed offline. A portion of the mixture is sampled and measured with an offline rheometer, tensiometer, viscometer, or goniometer to provide insight into the slurry properties and its wetting properties to the current collector [16]. During slurry dispensing for coating, the pipe pressure can indicate slurry viscosity; however, this is post-mixing and could result in more material waste than if nonconformities were caught during the mixing process when prescribed mixing parameters and solids content can still be tuned. To characterize the presence of agglomeration and/or coarse particles, fineness of grind tests (e.g., Hegman gauge) can be performed where a blade is used to manually scrape slurry along a marked stainless-steel block [30]. Several audit methods are used to check slurry quality prior to coating and drying, including Raman spectroscopy for active material uniformity, particle size distribution for mixing completeness, microscopy at various length scales for inspection, and thermogravimetric analysis to identify the slurry constituents.

**Opportunities in Nondestructive Evaluation:** Rheological and particle distribution measurements only enable partial characterization and conformance verification. While it is reasonable to presume that an inhomogeneous mixture would influence, for example, the viscosity, such a measurement is not a direct detection of the nonconformity. Furthermore, a slurry sample is inherently an audit. Additionally, the presence of foreign debris or contaminants would not be captured in the rheological measurements.

NDE opportunities in mixing therefore exist in the following areas: 1. In-situ rheological measurements, 2. direct characterization of particle dispersion characteristics, and 3. direct debris detection. Any implemented NDE technique should be in-situ and sufficiently automated to remove tedious and laborious measurements.

### 2.1.2. Coating and drying

**Process:** Coating and drying involves uniformly distributing the slurry on a foil current collector before passing through a multi-section oven to remove the solvent. It is common to refer to the current collector as a “web” in roll-to-roll processes, so that terminology will be used here. Slot die coating is the preferred coating method for high-rate production. Multi-section ovens are used to remove solvent from the coating via a combination of hot air convection, infrared radiant heating, and laser radiation [32]. Together these processes result in a durable dry coating. The final coating is 50–200  $\mu\text{m}$  thick and contains the desired areal loading of active material.

There is a wealth of research on slot die coating methodologies for a variety of industries including hydrogen fuel cells [33,34], solar cells [35], and paper coating [36,37]. The key process parameters that influence the coating thickness are the pump speed of the slurry, the slot die gap, and the web line speed. For battery cells, coating widths can be up to 1.5 m wide. The coating process relies on the non-Newtonian fluid properties of colloidal suspensions. As noted in the previous section, this enables it to be spread uniformly at low viscosity under higher shear before becoming stable with high viscosity once it is on the web at minimal shear.

In the drying process, oven length is the limiting factor for line speed. To achieve 50+ m/min line speeds [14] with drying times on the order of 3 min [38], industrial scale ovens are on the order of 150 m long. Fan speed, temperature, and radiation power are the main parameters adjusted to optimize the multi-stage drying process [32]. First, the thickness is reduced as solvent is removed from the slurry suspension to a point where the solids provide a framework of pores. The solvent is then pulled through the pores by capillary forces as it evaporates from the surface of the coating until the coating is dry [39]. In processes with NMP (common in cathodes), solvent recovery systems are added to reduce cost and environmental impact [40].

**State-of-the-Art Nondestructive Evaluation:** The influence of coating and drying on the electrode quality has driven the development of several, now commonly implemented, NDE methods. A good coating and drying process results in a uniform wet slurry coating onto the current collector and subsequent removal of the solvent without disrupting the homogeneity of the slurry constituents. It is crucial that the coating conforms to design specifications because it significantly influences the cell capacity and power density [41]. The two key influencers of cell performance are active material loading and dry coating porosity. Active material loading on an electrode is the measure of electrochemically active material weight or cycling capacity per unit area (in  $\text{mg}/\text{cm}^2$  or  $\text{mAh}/\text{cm}^2$  [42,43]) on the current collector. The coating porosity is reported in percent and influences downstream process parameter targets, namely in the calendering step [44]. The dry coating porosity provides a starting point and maximum value for final design targets in the power density vs energy density tradeoff [42].

Active material loading and dry coating porosity are difficult to measure directly; therefore, it is common to estimate them based on overall electrode mass loading and coating thickness measurements [45]. These measurements can be taken offline in an audit fashion by punching a sample, weighing it, and measuring its thickness via a drop gauge [46]. The active material loading and dry coating porosity are then estimated based on the percentages of the constituents as defined from the slurry mixing formulation. The accuracy of using electrode mass loading and thickness to estimate active material loading and dry coating porosity therefore relies on assumptions about the slurry compositional homogeneity and the measurements of the weight of the solid components in the mixing process step [45]. Note, this assumption is not necessarily a poor one thanks to the stability of the process. One drawback, however, is that it requires a punched sample to be removed from the coated electrode for measurements.

Inline nondestructive measurements for electrode mass loading and coating thickness also exist. Electrode mass loading can be quantified inline by measuring attenuation and backscatter of different forms of

radiation. The most common is the use of electron emission from radioactive isotopes (beta radiation) and its attenuation through the coating with a so called “beta gauge” [47]. X-rays have been shown to also be a useful source of radiation for measuring the mass loading of the electrode coatings via through transmission and backscatter configurations [48]. Inline coating thickness measurement techniques comprise various light-based measurements including laser triangulation [49] and laser calipers [50], which provide high bandwidth measurements while being minimally intrusive to line operation. Laser methods have the drawback that they can only access one side and must compare to the bare foil for a measure of thickness [49]. Recently, terahertz sensors have reportedly been used to estimate coating density, thickness, and conductivity at high rate with good spatial accuracy [51].

It is also important to nondestructively inspect for coating defects since the coating quality directly impacts the electrode cycling and power performance. Defects from upstream processes can be propagated through or amplified in the coating and drying steps. Inhomogeneities in the slurry, such as air bubbles and particle contaminants [52], are examples of defects that are passed through to the dry coating. Agglomerations of slurry constituents are amplified during coating. An agglomeration the size of the slot die gap can cause streaks in the deposited coating, requiring that portion of the coating to be scrapped [53]. Smaller agglomerations can introduce areas of low or high porosity and regions of decreased binder concentration. These defects can lead to adhesion issues, coating uniformity deviations, and variations in coating porosity or thickness [53]. Visible light cameras are commonly employed to identify air bubbles and streaks with either human inspection or image processing for quality decisions [54]. Infrared cameras are also used in through transmission or same side configurations to look for variations in coating absorption and emission properties separately from the reflectivity in the visible part of the spectrum [50].

Thickness variation from line speed drift or pump rate instability will cause variations in electrode loading [52]. In plants that use skip coating, edge bead quality is affected by mixing process step variations [49]. Contaminants in the plumbing can result in overly porous coating areas [52]. As mentioned in the mixing section, pairs of pressure sensors in the plumbing between the pump and the slot die provide in line information on the viscosity of the slurry thanks to the friction of the slurry against the walls of the pipes [30]. Another technique in use is to image the coating bead between the slot die and the web to watch for an unstable bead which causes spatial variation in the coating thickness.

Some drying defects can have more detrimental outcomes to the electrode batch than the coating defects. Drying at high rates can disturb the uniform distribution of binder and affects electrode durability [45]. Surface cracking can occur if thick coatings are dried too quickly [52]. Over-drying occurs when too much solvent is removed from the coating causing it to become brittle [39]. Under-drying leaves excess solvent in the coating which in turn increases the time required for vacuum drying, reducing plant level throughput. Infrared sensors can be used to measure the coating surface temperature and identify the transition from the 2nd to 3rd stages of drying [55]. For coating adhesion properties, offline peel testing of an electrode sample remains the method of choice.

**Opportunities in Nondestructive Evaluation:** Opportunities for NDE development targeted at coating and drying should focus on low-cost inline processes that increase accuracy, expanding property measurement to mapping rather than spot checking, and enabling tighter closed loop control of process parameters. For thickness measurement, adding a wet coating measurement would enable earlier detection of process variation, reducing scrap if the process moves outside the target window. For active material loading at this stage, enabling a mm lateral resolution 2D map of the electrode density of dry coatings offers an opportunity to verify conformance to design specifications and identify local density variations (agglomerations) before calendering where they are currently detected. The required thickness measurement accuracy will depend on the overall required coating thickness, but it is generally preferred to measure thickness with low single-digit micron accuracy.

Promising new technologies, such as terahertz imaging [51], which claim to nondestructively measure density should also be further developed and explored. In addition to expanding current techniques, inventing new methodologies that can directly measure design specifications determined in coating and drying including active material loading weight (as opposed to total coating weight) and dry coating porosity (as opposed to coating thickness) would be significant improvements over the current state of the art. Finally, there are currently no technologies to nondestructively inspect adhesion. A method to nondestructively quantify coating adhesion *in situ* or as an audit remains a difficult problem but would strongly benefit the quality verification process.

### 2.1.3. Calendering

**Process:** Once coating and drying is complete, the calendering process begins. Since the roll-to-roll speeds may vary between processes, the roll is rewound at the completion of coating and drying and transported to the calendering station. Calendering involves compressing double-sided coated electrodes with a pair of compaction rollers to achieve desired coating pore structure and porosity. See Fig. 3. The gap between the rollers is based on the desired coating porosity and is different for anodes and cathodes [44]. The final required electrode thickness is dependent on the slurry chemistry and can range between 20 µm and 300 µm, with a porosity reduction of around 40% [44]. One challenge in selecting appropriate calendering process parameters is to minimize mechanical stresses on the coating and web while achieving the target volumetric energy density [56].

Calendering is one of the most influential manufacturing processes on cell electrochemical performance. Compaction-induced porosity reduction increases volumetric energy density. It also decreases electrical resistance, thereby increasing power density. Compaction also improves cycling stability by reducing coating plasticity [44]. The specific capacity, however, decreases with level of compaction due to increased level of closed pores [56].

**State-of-the-Art Nondestructive Evaluation:** It is crucial that inline nondestructive evaluation techniques be implemented to monitor conformance, namely the porosity. The preferred method for estimating coating porosity level is by quantifying coating thickness and using known mass-loading. Note, this assumes that the coating is incompressible, though this is not necessarily true [44]. Laser micrometers, placed transverse to the calendering direction, can provide accurate thickness measurements, though the small laser spot size prohibits large scan area thickness measurements. Mechanical or digital dial indicators can also measure thickness. These latter tools require surface contact, therefore

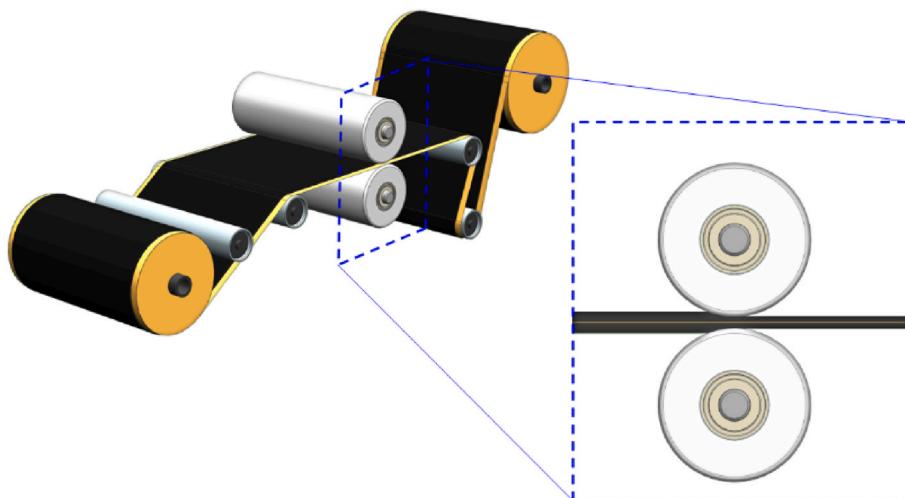
are generally performed as an audit or when the roll press is stopped. Coating uniformity may be measured using beta-backscattering; however, beta gauges generally have poor spatial resolution and require multiple units if it is necessary to distinguish the coating from the substrate. Additionally, due to atomic decay beta-gauge measurements can be noisy. Furthermore, a re-calibration is required for any mass-loading changes in the upstream mixing process.

In addition to conformance, it is important to inspect for any defects. The mechanical stresses during calendering can be quite high and can result in defects if the web yield strength is exceeded. The most common calendering defects fall into three categories as classified by Gunther et al. [57]: 1. Geometric, 2. Structural, and 3. Mechanical defects. These defects are outlined in Table 1. For visibly presenting defects (see Fig. 4), vision-based systems can often be employed.

All defects listed in Table 1 have some impact on subsequent production steps or battery cell performance. For example, geometrical defects negatively impact electrode stacking, which requires precise positioning [58]. In addition to the defects described in Table 1, any foreign debris and particle agglomeration can also be revealed at this stage since compaction increases their visibility on the electrode surface. The presence of large debris, e.g., larger than the thickness of separator, could cause separator puncture during subsequent electrode stacking. Any nonplanar geometry electrode defects, such as corrugation, affect other handling process such as cutting and gripping [57]. Mechanical and structural defects primarily affect battery cell performance because delamination and cracking yields areas of electrode inactivity and lithium plating.

Aside from vision, direct thickness measurement, and beta gauge, other various NDE techniques are reported in the literature. Etiemble et al. [48] demonstrated successful X-Ray radiography measurements for inspecting electrode quality in an area of several square centimeters. They achieved an in-plane resolution of 20 µm. Wood [59] demonstrated the use of thermography for detecting coating surface uniformity as well as defect detection. They also explored the use of XDR, XRF and TEM.

**Opportunities in Nondestructive Evaluation:** Considering the relative importance, many opportunities exist for NDE of post-calender coating thickness, porosity, and density. Although vision can detect some external defects, it cannot convey information pertaining to the mechanical or electrical performance of the electrode. Beta gauge can provide information about surface uniformity but suffers from low spatial resolution, noise, and cannot be used to check for active material delamination. Researchers considering entering this domain may consider reviewing existing NDE and measurement techniques for thin-



**Fig. 3.** Schematic representation of the calendering process, where compaction rollers are used to compress a double-sided coated electrode to achieve the desired coating pore structure and porosity.

**Table 1**  
Calendering Defect Types as classified by Gunther et al. [57].

Defect Category	Geometric	Structural	Mechanical
<b>Examples</b>	<ul style="list-style-type: none"> <li>• Electrode corrugation: periodic waviness along the calendering direction of the entire electrode surface</li> <li>• Corrugation: periodic waviness along the calendering direction which occurs between the coated and uncoated regions</li> <li>• Foil embossing: wrinkling along the uncoated foil edge</li> <li>• Saber effect (or camber or banana effect): the curvature of the electrode perpendicular to the rolling direction which results in electrode widening and wrinkling</li> </ul>	<ul style="list-style-type: none"> <li>• Local thickness and density variations: The calendering process exposes problems with mixing (e.g., inhomogeneous slurry) and/or coating (e.g., uneven coating) processes, since they become visible on the electrode surface after calendering.</li> <li>• Sealed surface pores: Indicated by visible high gloss sheen on the coating surface. It is further exacerbated by slurry binder migration to the surface.</li> <li>• Coating delamination: detachment of coating from the substrate</li> </ul>	<ul style="list-style-type: none"> <li>• Cracking of the coating and the substrate</li> <li>• Foil tears: caused by high line loads and agglomerates resulting in local increase of roller pressure</li> <li>• Electrode embrittlement</li> <li>• Aggregate: appear as hard spots on the coating surface</li> </ul>

film applications, such as those reviewed by Piegari and Masetti [60]. Finally, as in coating and drying, terahertz imaging [51] should be further developed and explored.

#### 2.1.4. Slitting and Notching

**Process:** Whether continuous or intermittently coated, the slitting step involves dividing the large calendered roll (mother roll) into several smaller rolls (daughter rolls) via rolling knives [61] or laser cutters [62]. The daughter rolls are cleaned of any cutting byproduct, rewound, and then vacuum dried to remove residual solvents and moisture.

Electrodes are finalized for stacking by cutting them with a notching

die or laser so that the bare foil portion of the electrode is “notched” to form a foil tab. At this step, electrodes may also be blanked into single electrodes, depending on the stacking technique. Electrode geometry depends on the coating pattern and battery cell design.

**State-of-the-Art Nondestructive Evaluation:** Slitted and notched electrode conformance consists of dimensional accuracy, coating alignment, and edge quality. The electrode should not contain foil tears, coating defects, or contamination. Dull cutting blades can cause poor foil edge quality, while die sticking can cause tab tears. Laser notching and slitting has been slower to adopt due to the resulting heat affected zone as well as byproduct/dust generation. If not properly controlled, such debris can lead to future electrical shorts. Slitting and notching dimensional accuracy and alignment accuracy can be validated with vision systems.

**Opportunities in Nondestructive Evaluation:** Most NDE research opportunities in this domain are around debris detection. Since this is the final step of the electrode manufacturing process, there is potential to detect many of the upstream issues at this point.

## 2.2. Cell assembly

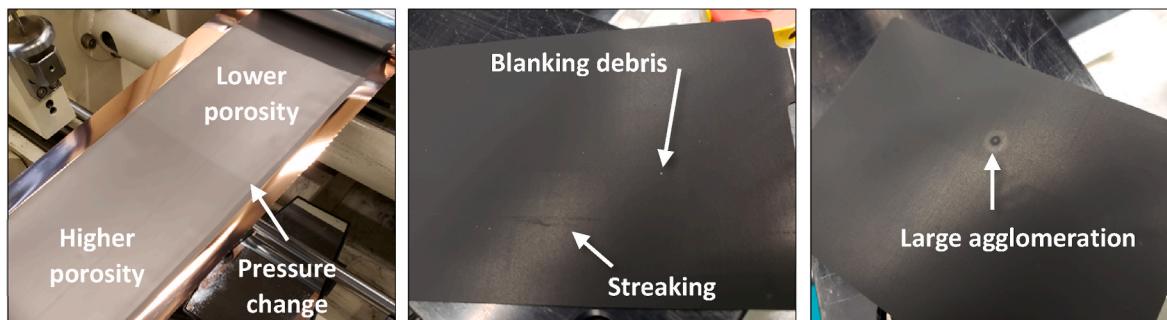
The second major step of the cell manufacturing process transitions from the fabrication space to the assembly space and is denoted “Cell Assembly” as outlined by the gray portion in Fig. 2. Cell assembly begins with electrode stacking and concludes with electrolyte fill and pouch sealing and is done in a dry room environment where the dew point is typically held to  $-40^{\circ}\text{C}$ . The output is an assembled, but not yet electrochemically active, battery cell. Since cell assembly involves joining components, conformance specifications are weighted more toward structural integrity than in electrode manufacturing and accordingly there exists a different set of applicable NDE techniques.

Unlike electrode manufacturing, cell assembly contains many stations where the cell is semi-stationary, such as during welding, pouch lamination, or electrolyte fill. Still, these processes are typically on the order of a few seconds, and so any inline NDE technique must operate accordingly. If excessive cycle time is not introduced, separate NDE stations can be used, where cycle time constraints are set based on required plant throughput.

Weld inspection is the largest NDE research opportunity. As in any system, the welds are often a potential “weak point” and must be inspected to verify that they are electrically and structurally sound. Battery cell welds are especially complex from an NDE perspective because they are multi-layer (15–50 foils joined to a tab), thin ( $<2\text{ mm}$  thick), have complicated surface geometry, and must be inspected with a non-contact technique. Additionally, inspection must be quick to ensure that manufacturing throughput is maintained.

#### 2.2.1. Stacking

**Process:** Once manufacturing of the anodes and cathodes is complete, they are ready to be assembled into an electrode stack. There are a multitude of folding and stacking techniques, where the basic objective



**Fig. 4.** Examples of various structural defects which become more visible after calendering.

is to precisely position alternating anode and cathode electrodes with separators between each layer. See Fig. 5. Intermittently coated current collectors are often blanked from the roll and stacked (Fig. 5 (a)). Continuously coated current collectors may be folded or wound (Fig. 5 (b)). Folding may consist of a so-called “Z-fold” (Fig. 5 (c)) where the separator is continuously folded back and forth, while electrodes are inserted one at a time, or in the form of short stacks of electrodes and separators. Finally, pre-stacked electrodes and separators can also be folded with a continuous separator as shown in Fig. 5 (d) [63].

**State-of-the-Art Nondestructive Evaluation:** Vision systems are the predominant mode of NDE for electrode stacking and are used to detect holes, tears, and stack alignment issues. Dimensional accuracy checks, edge alignment, and electrode sizes can also be monitored with vision. After stacking, an isolation check confirms that the anode and cathode do not have a short circuit.

Alignment and stacking accuracy are critical to cell assembly. The anode must overhang the cathode on all sides to prevent lithium dendrites [65,66]. The separator should provide good coverage between the electrodes, without wrinkling or tearing. Equipment maintenance and cleanliness are needed to avoid stacking debris into the cell. Improper material handling can introduce unintended folds or damage to the electrodes or foils [67]. Many defects which become evident during formation or during battery cell use have the potential to have originated during stacking. These defects include holes, tears, foreign debris, or misfolded electrodes or separators.

Robinson et al. [68] used ultrasonic acoustic measurements to detect large defects such as a partially missing electrode or large uncoated region in the stacked electrodes. Although it was possible to observe defects, couplant was needed for this study which would not be easy to implement during cell assembly. Kong et al. [65] used X-Ray computed tomography (CT) to look at completed Li-ion battery cells along with other destructive tests. They observed defects such as a folded current collector, cathode overhanging the anode, and deformation caused by the assembly process which damaged areas of the electrode coating.

**Opportunities in Nondestructive Evaluation:** Many of the opportunities in NDE for electrode stack conformance/defects would benefit by being placed immediately succeeding electrode stacking or further down the line. Inline CT would enable electrode stack defect detection. Such an inline CT system could be placed either directly after stacking or further down the line, since the pouch material is nearly “invisible” to x-ray photons. Though there have been groundbreaking improvements in CT speed [69–72], there are still significant advances that must be made before it can be considered as an inline technique or even as a separate

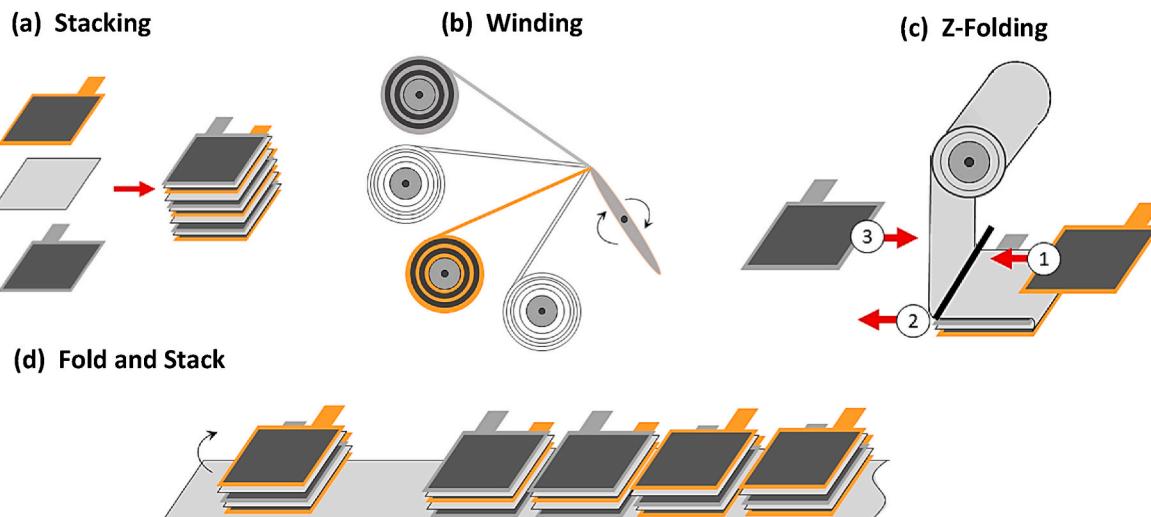
offline station in the battery industry. To be considered appropriate for inline use, the speed would need to accommodate <5s cycle time at an appropriately high resolution (for example, <15 μm voxel size for anode inspection). In their current form, folded separators cannot be detected using x-ray due to its very low density and thickness relative to the surrounding materials. Direct 2D radiography should also be considered since the reduction in cycle time may offset the loss of 3D information. A nondestructive technique to detect folded separators in a completed electrode stack would prove very beneficial. Finally, detection of debris, such as unintended metal or polymer, is important. Large metallic debris may be detectable via x-ray.

## 2.2.2. Welding

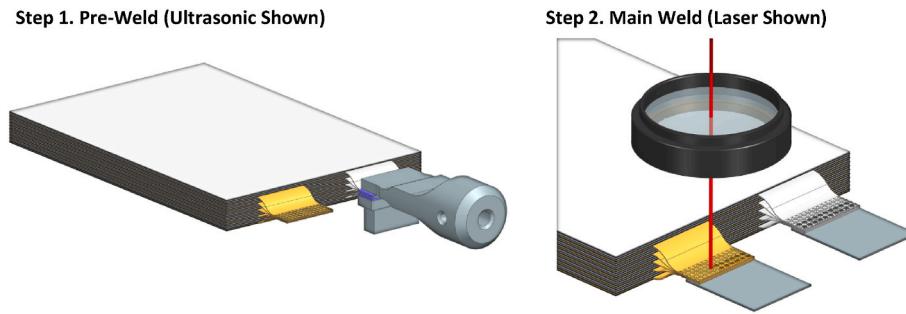
**Process:** The final step in electrode stack assembly is to join the external tab to the electrode foil tabs that were created during notching. There are two welds: an aluminum battery tab is welded to the bare aluminum cathode current collectors and a copper battery tab is welded to the bare copper anode current collectors. The battery tabs are typically a thin plate or bar. They may be on opposite sides or the same side of the cell. These tab-to-foil welds are commonly referred to as “internal welds,” since they reside inside the pouch upon cell completion.

Since electrode stacks consist of many foils (e.g., 15–50 aluminum and 15–50 copper foils), welding is usually a two-step approach where the foil tabs are first gathered via a pre-weld and then joined to the external battery tab. Welding is usually ultrasonic, laser, or a combination thereof, and the entire process is only a few seconds. Fig. 6 contains a schematic representation of this 2-step welding process. The thickness of the foils is typically on the order of 10 μm, and the tab thickness generally varies from 0.1 to 0.6 mm. Fig. 7 (a) contains an example of an electrode stack immediately post-welding. A cell in this condition is often referred to as a “dry cell.” Fig. 7 (b) contains various electrode foil-to-tab weld coupons, including ultrasonic (welded by Tech-Sonic [73]) and laser welds. Although only ultrasonic and laser welds are discussed here, the reader should be aware that this is an evolving field, and many multi-layer joining strategies exist [74–76].

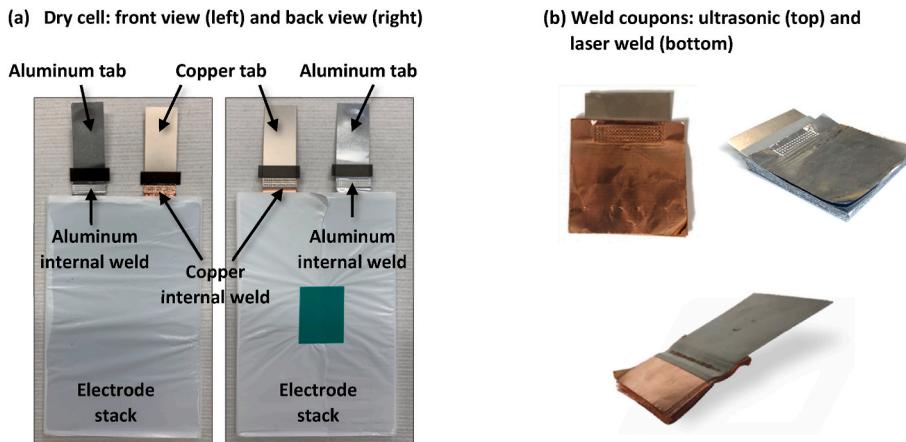
**State-of-the-Art Nondestructive Evaluation:** Nondestructive inspection of internal welds involves verifying weld conformance as well as detecting any defects, where specific conformance standards and defect types depend on the type of weld. Although nondestructive inspection methods are used and will be discussed in the succeeding text, the most common form of inspection for internal welds is destructive testing audits where a cell(s) is pulled from the line and mechanically tested for strength.



**Fig. 5.** Electrode stacking by (a) stacking, (b) winding, (c) z-folding, and (d) folding and stacking bi-cells. (Image (a,b,c) adapted from Schroder et al. [64] and (d) from Ahn et al. [63]).



**Fig. 6.** Schematic representation of Step 1, the pre-weld (shown as ultrasonic), followed by Step 2, the main weld (shown as laser).



**Fig. 7.** Multi-layer electrode foil-to-tab welds shown in (a) a dry cell and (b) ultrasonic and laser weld coupons. The ultrasonic weld coupons in (b) were provided by Tech-Sonic [73].

Ultrasonic welds are solid-state welds and typically experience defects such as tearing or cracking. Laser welds require melting of the material and are more likely to have porosity. Both types may experience weak bond conditions or insufficient penetration. Regardless of type, the welds must be both electrically and structurally sound. In addition to field performance, they must maintain integrity throughout the entirety of the remaining manufacturing processes. An acceptable weld is governed by design criteria based on its intended performance. For example, design requirements may specify maximum electrical resistance and minimum pull strength. While the modalities are different, many of the factors that contribute to low electrical conductivity (high resistivity) also contribute to low strength. This is because, a larger weld area generally yields higher strength [77]. A larger weld area also leads to lower resistivity (the current density decreases as the area increases) [77]. For bond strength, a weld with high porosity will suffer from both a reduction in strength and an increase in resistance. This bond strength/electrical resistance relationship, however, breaks down in cases where the joint forms a good electrical connection, but does not have a strong structural connection, such as in a kissing bond where the faces are only in contact under compression. It is important that the foils remain intact and do not contain any discontinuities. The foils are extremely delicate; points of over-strain are undesirable since they behave as localized stress concentrations or potentially tear initiation points.

The measured electrical resistance of the weld is therefore one metric that can be used to assess weld quality. Resistance measurements can be used to detect abnormal welds; however, the low resistance ( $\mu\Omega$ ) makes it challenging to obtain measurements that are sensitive enough to detect nonconformities while remaining insensitive to test variations such as probe placement. McGovern et al. [77] presented electrical resistance results for larger format ultrasonic welds. A correlation was

observed between weld area and measured electrical resistance. Such a technique is more difficult to employ on internal foil welds, since even very light probe contact can cause the delicate foils to bend and alter the measurement, or at worst, inflict damage.

Process monitoring systems are also commonly used as an indirect approach to infer weld quality during the welding process [78]. Though rare, one defect that can occur is that one or more foil(s) do not make it into the weld stack. Some ultrasonic metal welders (e.g., Branson, Tech-Sonic) use a “closed loop technology” system which measures the sonotrode height pre- and post-weld. In doing so, they can detect missing or bent foils, incorrect gauge, or damaged materials [73,79]. Laser welding can be monitored with backscattered light sensors [80]. Traditional vision systems can also be implemented; however, these are limited both due to inherent errors caused by reflectivity and inability to see subsurface flaws.

Many conventional weld inspection techniques are applicable to ultrasonically welded internal welds since the principle is generally that of monitoring delamination and bond area. The difficulty arises in their relative thinness and complex geometry. Ultrasonic welds have a complicated geometry comprised of a periodic series of peaks and troughs, the pattern of which is dictated by the weld horn and anvil. Weld quality is commonly discussed in the context of the welding parameters (pressure, amplitude, and time or energy). It is very common to refer to nominal (acceptable), under-, or over-welding as an indication of the weld quality. Under-welding results in insufficient bond strength, or in the worst case, no connection. Over-welding results in excessive material thinning and potential cracking or perforation, particularly in the top current collector which contacts the ultrasonic horn. Misalignment of the weld horn with the anvil can also occur, which results in a nonuniform pressure distribution yielding non-uniform bonding across the weld. Areas of disbond or delamination can also occur in ultrasonic

welds. The reader is referred to Arimoto et al. [81] for micrograph which show representative examples of ultrasonic weld cross-sections.

McGovern et al. [77] showed success in larger format ultrasonic welds with thermography. They were successfully able to measure weld bond area and showed a correlation between thermal signal strength, bond area, and bond strength. They also introduced a thermal gradient image technique to successfully identify difficult-to-see cracks in over-welds.

Bruder et al. [82,83] demonstrated through-transmission thermography to be a promising technique for ultrasonic internal welds. Through-transmission thermography was performed on electrode-stack ultrasonic welds pre- and post-subjecting them to an aggressive, damaging vibration force. For the same weld, thermal measurements showed less thermal conductivity post damage than in the original state. In the same paper [82], they also showed limited success with laser-induced ultrasonic total focusing method [84]; however, the defects were limited to point reflectors and the signal was highly scattered due to the ultrasonic weld geometry.

For laser welds, many of the conformance standards used for structural vehicle body welds apply, such as depth of penetration, nugget size, concavity/convexity, etc. Excessive or insufficient power can cause over- or under-weld conditions, respectively. Since laser welding is a thermal process, shrinkage cracking can occur in the heat affected zone resulting in foil detachment from the laser weld nugget. Weld spatter can also occur and is important to minimize because it removes material from the weldment and may introduce contamination to the electrode stack. Finally, porosity should be minimized since it is directly proportional to electrical resistance and inversely proportional to weld strength. See Fig. 8 for laser weld defect examples. There are currently no published methods for nondestructively inspecting multi-foil laser welds.

**Opportunities in Nondestructive Evaluation:** Due to the lack of research on NDE of these very thin, multi-layer foil welds, there is ample opportunity to address gaps in this area. It is also not a one-size-fits-all approach since, as discussed above, ultrasonic welds typically have different defect types than laser welds.

Since there is very little research, it is worth saying a few words on the constraints under which any NDE technique should operate. Depending on the point in the manufacturing process, the welds may or may not be directly accessible for nondestructive measurements (e.g., dry cell vs. fully assembled cell). Immediately upon welding, the welds are fully accessible and there is access to both sides, see Figs. 6 and 7. Note, isolation tape is placed on the weld shortly after welding to protect the pouch from wear of the rough weld. Quality verification techniques do not necessarily have to be non-contact; however, any contact with the sample should not alter its state. Excessive contact pressure between a probe and the sample could cause damage to the extremely delicate foils. The use of ultrasonic couplant is not desirable since it would be very difficult to remove and could have deleterious effects downstream.

Inspection of laser-welded internal welds presents an even more difficult problem than inspection of ultrasonic internal welds. Recall, foil detachment is a known defect (Fig. 8 (b)). This means that a traditional through-transmission thermography approach may not be suitable: while thermal propagation serves as an indicator for the laser weld itself (e.g., detect excessive porosity, major delamination, etc.), it would not detect foil disconnections in the lateral direction. An ultrasonic approach, like the one described in Bruder et al. [83], would fail for multiple reasons: 1. There is no acoustic impedance mismatch between the weld nuggets and battery tab to allow for reflections; 2. Any reflected signal would be difficult to detect since the ultrasonic wave would need to traverse a complicated path to reach the location of foil detachment; and 3. The very thin nature of the foils (~10 μm) would necessitate an unachievable high frequency to resolve foil detachment (e.g., ~1.2 GHz for a ~6130 m/s longitudinal wave in aluminum). X-Ray CT scans, while useful for validation, are lengthy and do not result in a sufficient resolution (<10 μm voxel size) unless the weld is destructively sectioned from the cell to remove excess material and enable positioning close to the x-ray source.

Inline NDE for multi-layer foil welds is not well understood and there remain large knowledge gaps to fill, hence ample research opportunities. This is especially true for foil detachment detection in laser welds. While it is always preferable to develop technologies that work under the most severe of constraints, such as nondestructively detecting foil detachments in a fully assembled cell, there would still be great value in NDE technology that could inspect such issues even under lighter constraints such as for a dry cell where the weld is accessible from both sides. The internal weld geometries, accessibility constraints, and defect types pose large challenges, but the reader is encouraged to refer to research that has published for NDE in other thin, metallic electrical joints for inspiration and starting point [77,85,86].

### 2.2.3. Packaging and electrolyte fill

**Process:** The final step in the cell assembly process involves introduction of the pouch material and electrolyte. The pouch material is sealed on three sides around the electrode stack such that the battery tabs protrude. The seal is achieved either by laminating three sides or by folding the pouch material in half and laminating two sides. The pouch material is a flexible, multi-layer, electrically insulating, composite structure comprised of aluminum and polymer layers. Electrolyte solution is filled through the open side of the pouch and the fourth side is sealed off via lamination. Cells can be weighed before and after electrolyte fill to ensure the proper amount was added. Excess pouch material permits battery cell degassing, which will be described in Section 2.3.2. The electrolyte wetting process takes hours to days to fully penetrate and wet the entirety of the electrode stack. Wetting is alternatively referred to as aging.

**State-of-the-Art Nondestructive Evaluation:** The incoming electrolyte liquid must conform to the appropriate constituent proportion,

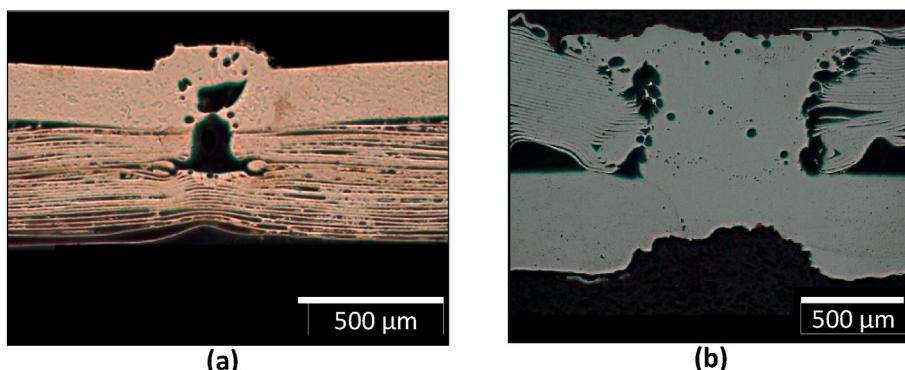


Fig. 8. Battery foil to tab laser welds with (a) insufficient penetration and high porosity and (b) foil to weld bead detachment.

viscosity, salt concentration, and water content (ideally 0 ppm of water). Full electrolyte wetting of the electrode stack must be achieved prior to formation (Section 2.3). Improper wetting is detrimental to the cell performance, cycle life, and safety profile. Improper wetting leads to nonuniform solid electrolyte interface (SEI) layer growth during formation, which will be discussed in the next section. This results in electrolyte decomposition as well as decreased Coulombic efficiency. It also precipitates conditions favorable to lithium dendrite growth. The presence of unfilled pores yields non-uniform Li-ion transport leading to non-uniform current densities, areas of overpotentials, and decreased effective lithium conductivity [87].

Currently, viscosity and surface tension are the only measurable metrics used to estimate electrolyte wetting performance [88]. In 2015, Sheng [88] developed a wetting balance method to quantitatively measure the wetting rate.

Peter et al. [89] demonstrated a chronoamperometry approach for in situ electrolyte wetting determination. More recently, ultrasound has been a method proposed to estimate wetting conditions. Deng et al. [90] demonstrated that peak-to-peak ultrasonic amplitude scans could be used to estimate the wetting condition under the principle that “unwetted” areas would result in higher attenuation and hence lower amplitude. They also demonstrated that reflection/transmission coefficient measurements yielded similar results. The ultrasonic scans were performed by immersing the cells and transducers in a low-viscosity silicone oil. Liminal Insights Inc., formerly known as Feasible, uses ultrasound and machine learning to estimate wetting condition [91]. Their device uses dry couplant. While ultrasound has shown promise, there are cycle time and repeatability considerations. Ultrasonic amplitude measurements are highly dependent on couplant conditions. The presence of gas, while important, will also impede any efforts to glean the wetting condition. Finally, ultrasonic c-scans (i.e., area scans) are slow: even a relatively small scanning area of 1 in<sup>2</sup> can take minutes to scan for sufficient resolution, far too slow for a production setting. Finally, dry couplant typically requires pressure, which may pose an issue depending on the level required. Neutron imaging, though not suitable for inline inspection nor nondestructive (the part becomes irradiated), is a powerful technique that has been used to image electrolyte within a fully assembled cell to visualize and understand the wetting process [92].

With respect to the pouch, it is important that it remain structurally intact and provides a hermetic seal to prevent electrolyte loss and/or air intrusion. It should also provide appropriate external electrical insulation. For this reason, the pouch material should not be punctured or torn. Though unlikely to occur in this point of the manufacturing process, excessively rough handling during future shipping or manufacturing operations can result in a damaged pouch. Therefore, it may only be prudent to check for pouch defects only where rough handling is suspected or has the potential to occur. Depending on when the damage occurs, manual inspection of cells or later module/pack level electrical tests may detect this type of failure.

**Opportunities in Nondestructive Evaluation:** Whereas there are limited NDE research opportunities for the actual electrolyte fill process, electrolyte wetting is an area of strong importance. Even though this area is important, there exists only a very small body of published research on the actual wetting process, much less any associated nondestructive inspection techniques. The only way to ensure proper wetting is to allow the electrolyte enough time to fully penetrate the layers. This time allowance is typically on the order of days. An NDE technique to estimate or quantify wetting would not only serve as a useful quality check but also provide feedback to enable initiation of the formation process and consequently result in time-savings. Notwithstanding, it would be misleading to state that cell manufacturers would be likely to implement such a check for 100% inline inspection. Rather, the biggest opportunity for adoption would be during the development phase, prior to the actual manufacturing process when the process parameters are still being tuned.

## 2.3. Formation

Formation can be broken down into three processes: formation, degassing, and aging as shown in the green portion of Fig. 2. The output of this stage is a fully assembled, electrochemically active battery cell. For simplicity, the processes will be discussed in the order listed above; however, the steps can be interwoven depending on the specific cell manufacturer's preference.

Most NDE research opportunities in the formation stage must be applicable to a nearly completed cell. While this poses challenging constraints, the quick cycle time constraint is removed, since the cell is nearly or completely stationary for much of the formation process.

### 2.3.1. Formation (SEI creation)

**Process:** The formation stage consists of formation of the solid-electrolyte interphase (SEI) layer on the anode active material. Formation protocols are complex recipes involving precise pressure, temperature, and charging rate sequences to minimize formation time. There is a need to balance formation time and electrochemical performance of high energy Li-ion batteries. The details are closely guarded since it is the secret ingredient to cell longevity and performance. At a high level, the cell is slowly charged (~C/20 or C/10),<sup>2</sup> however, there is ongoing research to speed up this process, to enable electrolyte reaction with the anode active material [93,94]. The reaction products are gas and an organic compound [95].

The optimal SEI layer is thick enough to provide electrical isolation between the active material and the electrolyte, yet thin enough to allow Li diffusion [96,97]. If the SEI layer is too thin, the electrolyte will continue to react with the anode active material each time the battery is charged, leading to electrolyte dry-out. Electrolyte dry-out precipitates early cell failure from insufficient electrolyte to transport Li-ions during charging and discharging. It can also cause lithium plating from insufficient lithium capacity in the electrolyte. An excessively thick SEI layer results in poor rate performance from high internal cell resistance. A non-optimized electrolyte composition and formation recipe can yield a brittle SEI layer, which will crack from the expansion of the anode active materials during the charging process. This exposes “fresh” electrode to the electrolyte, which again leads to electrolyte dry out [98].

**State-of-the-Art and Opportunities in Nondestructive Evaluation:** Current inline inspection of the formation process can involve monitoring the cell response during formation protocols in comparison to a reference curve. For example, the cell response, e.g., voltage or current, over time can be measured.

### 2.3.2. Degassing

**Process:** During formation, gasses are produced as a by-product to the SEI formation. In pouch cells, this gas accumulates in the excess pouch (or “gas bag”) and is not needed for battery cell operation. After formation, the cell is placed in a degas chamber. The chamber pressure is pumped-down to a low pressure (e.g., single-digit PSI) and then the gas bag is punctured to remove the excess gas. The pouch is then resealed near the electrode stack while the cell is still in the chamber. Finally, the remaining excess pouch material is trimmed.

It is important to ensure that all excess gas is removed since the presence of gas bubbles can cause a non-uniform pressure distribution on the cell once it is in operation in a module under compression. A non-uniform pressure distribution will reduce cell performance.

Since the pouch must be sealed once the gas bag portion of the pouch is removed, it is also important to ensure that there is a proper seal.

**State-of-the-Art and Opportunities in Nondestructive Evaluation:**

<sup>2</sup> The C/20, C/10 designations is the commonly used “C-Rate” designation. This describes the charge/discharge rate for a 1Ah (1C) rated battery, where 1Ah provides 1 A for 1 h. Thus, C/10 and C/20 describe 10 h and 20hr charge/discharge rates.

Currently, there are no inspection techniques for monitoring the degassing process. Rather, process monitoring of the chamber itself is performed to ensure that the chamber reaches vacuum. The final pouch seal can also be checked for proper sealing at this time.

### 2.3.3. Aging

Since aging is a quality verification step, this section will not be divided into multiple parts like the preceding sections. By floor space, aging is the single largest battery cell manufacturing process and process time bottleneck [99]. During aging, cells are connected to the cycler and the open cell voltage (OCV) is checked over time without passing current through the battery [96,100]. If the voltage falls faster than a pre-determined rate (mV/time), the cell is rejected. This is often referred to the “voltage droop” check. Voltage droop is checked prior to end-of-line testing (described in the next section).

While there is not total access to the cells from an NDE perspective, it should be mentioned that during aging, the cells remain stationary in a warehouse for a long period of time. Thus, there may be opportunity for NDE techniques during this step. The cells are housed in crates, the geometry and storage configuration of which depend on the manufacturing plant. The amount of cell access depends on plant itself and how they store the cells. For example, the cells may be stored so that there is only access to the cell tabs since that is all that is required for OCV check.

## 2.4. End-of-Line

The scope of this discussion begins immediately post-formation and ends at pre-shipped, fully assembled cells. Cells which are purchased from a supplier or obtained from a battery module/pack tear-down (post-mortem analysis) will not be discussed since it is after the cell manufacturing process.

**Process:** The end-of-line (EOL) step comprises quality control and aesthetic refinements. For aesthetics, the pouch “wings” (laminated seams) are folded and taped, cell faces can be smoothed via hot pressing, and labels are printed on cell faces. EOL quality verification testing is also done at this stage, the specifics of which will be described in the “Inspection” sub-section. Although aging is predominantly done prior to EOL testing, the aging step can be revisited after EOL quality verification testing based on plant protocol or EOL test results.

**State-of-the-Art Nondestructive Evaluation:** EOL testing for quality verification involves several techniques, many of which are electrical in nature and not traditionally categorized as NDE methods. Since EOL is essentially the last stage of the cell manufacturing process, every upstream characteristic, conformance criteria, and defect influences cell quality. Overall, the cell must be checked that it conforms electrically, structurally, and aesthetically. Cells are graded according to their capacity as measured from a charge/discharge cycle. The cell’s internal resistance is also measured via the “Direct Current Internal Resistance” (DCIR) method [101].

Hard and soft shorts may also be checked for at this point in the manufacturing process. Hard shorts occur when there is a direct connection between anode and cathode electrodes, resulting in high current flow and can result in complete discharge and irreversible cell damage. A hard short strongly increases the probability of a thermal runaway event [102,103]. A soft short is less well defined but is generally understood to be a less severe form of a hard short and is often intermittent [104,105]. For example, lithium dendrite growth can locally puncture the separator. This local dendrite acts as a bridge from anode to cathode, enabling electron transport, i.e., behaves as a micro-short. The resulting localized high current eventually destroys the lithium dendrite through melting/vaporization, which effectively removes the short and re-opens the circuit. A soft short of this nature is therefore intermittent due to its “self-correcting” behavior and often results in current “leakage” but does not necessarily result in thermal runaway. Soft shorts are notoriously difficult to detect, and to date, there

are no proven NDE techniques other than the so-called “rest and test” method where cells are held for a period of time and checked for voltage droop.

A pouch isolation check is also performed to ensure electrodes are electrically isolated from the pouch material by measuring the voltage between a battery tab and the pouch. To check pouch isolation, the pouch resistance is measured by applying a voltage from the pouch edge to the cell body. This test can be performed while the cell is under compression. A cell that fails this test may be root-caused to either, 1. A faulty pouch material such as a cracked internal layer causing the conductive middle layer to be in contact with the electrode stack; or 2. An electrolyte leak which completes the circuit from the pouch edge to the tab.

Any NDE techniques applicable to fully assembled cells, whether electrical, or a more traditionally classified NDE methods, should be considered based on application. Throughout the manufacturing process and during the life of the cell, all cell components must remain intact and in position. Though guarded against, defects can be introduced to the cell at any point in the manufacturing process from cell handling or sub-par manufacturing conditions. Excessively rough handling or poorly set manufacturing process parameters can result in various unintended defects such as electrode bends, weak internal welds, foil tears, separator folding, etc. Electrochemical abuse, such as overcharging, over-discharging, or shorts can precipitate lithium dendrite formation. They can also be precipitated from geometric defects such as nonuniform coating and contamination [100,106]. Research in nondestructive evaluation for fully assembled cells primarily involves electrical testing and application of traditional NDE techniques for defect detection. Sun et al. [100] discusses identifying Cu particle contamination using a short circuit resistance test, where internal shorts cause self-discharge. Davies et al. [107] used machine learning to predict the state of charge (SOC) in Li-ion pouch cells from ultrasound time-of-flight and amplitude data. They were able to predict SOC within 1% accuracy. The measurable effects on the ultrasonic waves were attributed to elastic modulus and density changes of the active materials during cycling. Keysight offers a self-discharge measurement device [108] which enables rapid evaluation, e.g., 1–2 h, of a cell’s propensity to self-discharge in lieu of a lengthy, e.g., weeks to months, OCV check. Examples of offline inspection techniques can include electrochemical impedance spectroscopy (EIS) [109–111] and galvanostatic intermittent titration technique (GITT) [112]. These tests are nondestructive if employed properly.

**Opportunities in Nondestructive Evaluation:** Although the opportunities for *inline* quality verification systems have been discussed at length in the preceding sections, inspection of fully assembled battery cells still presents ample research opportunities. Accessibility is a major testing constraint for a fully assembled cell since most of the components of interest now reside inside the pouch. All manufacturing process defects, even if already detectable with an existing inline NDE technique, may be useful to detect at EOL for redundancy since catching a cell that is at risk of suffering from early failure must be caught before it leaves the plant. One example of a promising NDE technique is rapid CT, as discussed in the “Stacking” section (Section 2.2.1).

Though lithium dendrite growth and plating would not occur in the cell manufacturing process without extensive electrochemical abuse, the detection of this defect is of such importance that it is mentioned here. While there is extensive research on lithium dendrites, there are, to date, no NDE techniques for early onset prediction/detection. Researchers considering entering this domain are referred to Janakiraman [113] for a thorough review of lithium plating detection methods.

## 3. Impact of future electrochemistries on NDE research needs

Beyond present-day mass-produced Li-ion pouch cells, there are a plethora of promising new electrochemistries and process improvements on the horizon. They promise higher energy densities, lower material costs, improved safety performance, and reduced manufacturing

complexity just not all at once. Although some of the outlined NDE methods apply, many of these changes present a new set of inspection challenges. First-time quality remains crucial to instill confidence in any new product and can only be realized with robust inspection techniques. This section will comprise a brief speculation of near-future (3–5 year) electrochemistries' impact on NDE technologies. A high-level summary of the electrochemistries themselves as well as useful references can be found in [Appendix B](#). The large-scale manufacturing processes for these future electrochemistries have not yet been defined; therefore, the following discussion will be necessarily high level and only enough detail will be provided to summarize important areas of which the NDE researcher should be aware. Note, while solid state electrolytes have gained great popularity in the research community, they will not be discussed here as there is not yet a near-future path for high-rate manufacturing.

Many of the aforementioned NDE techniques for Li-ion pouch cell manufacturing may still be applicable for part conformance inspection on future battery cell electrochemistries; however, changes in the manufacturing process itself may necessitate re-prioritization of existing quality verification techniques. For example, green solvent-based binder polymers will require that a stronger emphasis be placed on assessing the coating adhesion due to their reduction in performance. Prioritization of inspection techniques may also be driven by an electrochemistry's known predisposition to certain defects. For example, silicon and silicon-oxide anode active materials [114] exhibit increased expansion when cycling which causes mechanical fatigue cracking of the particles. These cracks open new surface area to lithium-consuming SEI growth resulting in severe capacity fade [115]. NDE techniques that can assess the presence of fatigue cracks should therefore be developed for quality verification of silicon and silicon-oxide anodes.

In some cases, entirely new NDE techniques will need to be developed. One such example is for blended cathode and anode materials. Current NDE methods for these blended cathode [116,117] or anode [118,119] materials are limited to offline audits via SEM/EDS for powder distribution uniformity. Similarly, dry processing techniques require offline audit SEM/EDS methods to assess powder purity and particle size distribution, because the elimination of solvent [120] renders current wet slurry inspection techniques, such as viscosity or slurry homogeneity, no longer applicable. New NDE characterization methods will therefore be necessary to ensure powder purity and particle size distribution for these two potential future electrochemistries. For PTFE based dry and semi-dry coatings, one area of opportunity is to develop an inline NDE technique to quantify the degree of fibrillation of PTFE polymers.

Electrochemistries involving lithium metal pose their own set of NDE inspection challenges. In its pure form, lithium is soft and mechanically fragile; therefore, any technique must be non-contact. Furthermore, its extreme chemical reactivity, especially with water, necessitating that NDE methods operate in dry (dewpoint < -40 °C) or inert atmospheres (Ar, vacuum). The high specific capacity of metal anodes [121] enables a significant reduction in electrode thickness (to 10s of microns) for Lithium metal anodes. This drives the requirement that any NDE technique used to measure thickness or thickness uniformity be very highly resolved (e.g., single-digit microns or less). In Si and SiO<sub>x</sub> containing anodes, the thickness of the prelithiation layer can be on the order of 10 μm or less, pushing the resolution needed even further than in lithium metal anodes. As the performance (cycle efficiency) of Lithium metal including anodes improves, thicknesses will reduce, forcing further improvements in the abilities of NDE techniques for confirming

properties.

Although new electrochemistries and manufacturing processes will require new NDE techniques, many NDE techniques suitable for inspection of Li-ion pouch cell manufacturing will still be applicable. Electrode quality indicators such as coating thickness, density, and porosity will still be important for electrode coatings, even if the electrochemistry or manufacturing process changes considerably. This is true for green solvents (e.g., biosolvents or water [122]), dry process electrodes [120], silicon and silicon-oxide anodes [114], and lithium metal anodes [121]. In any case, the NDE researcher should always consider the applicability of current NDE techniques, rather than preemptively spending effort on redeveloping an entirely new NDE technique.

#### 4. Conclusions

A paradigm shift for NDE technology research and development is required to keep pace with disruptive EV technology and the associated challenging inspection constraints. The goal of this paper was to provide a review of the current research needs for NDE in EV battery manufacturing, with a focus on Li-ion pouch cells. A brief discussion on potential near-future advanced manufacturing processes and electrochemistries was also provided. Li-ion battery manufacturing is a complicated process where every step needs to be defect free to produce an acceptable battery.

The constraints surrounding NDE for EV battery manufacturing are especially challenging because they must meet the demands imposed by a simultaneously existing set of individually demanding constraints including quick cycle times, thin parts, complex geometries, limited part accessibility, etc. Part accessibility can be increased by implementing NDE quality verification steps throughout the manufacturing process. Inline implementation has the additional benefit in that defects can be identified before allowing the battery to progress to the next step to minimize cost and scrap.

#### Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Megan McGovern reports financial support, administrative support, and travel were provided by General Motors Global Research and Development - Manufacturing System Research Lab. Megan McGovern reports a relationship with General Motors Corp that includes: employment.

#### Data availability

No data was used for the research described in the article.

#### Acknowledgments

The authors would like to thank Andy Oury and Warren Parsons for their help in creating the accompanying presentation at the ASNT Research Symposium. Also, a large thanks to the ASNT members for useful feedback, especially Professor Reza Zoughi and Professor Henrique Reis. Thanks also go to Nick Irish, Nicole Ellison, Dr. Debejyo Chakraborty, and Dr. Tom Yersak for pictures, Dr. Sen Xiang for micrographs, as well as Dr. Shaomao Xu, Dr. Raffaello Ardanese, Dr. Mike Wincek, and Dr. Robin James for helpful discussions. Finally, thank you to John Hall from Tech-sonic for providing internal weld images.

## APPENDIX A. Glossary of terms

**Table 2**

Glossary of Terms.

Term	Definition
<i>Current collector</i>	Aluminum or copper foil portion of the electrode.
<i>Web</i>	Otherwise known as a current collector foil. This designation is typically used when within the roll-to-roll context.
<i>Electrode</i>	The coated current collector. Either anode or cathode.
<i>Anode</i>	Coated copper current collector. Negative electrode.
<i>Cathode</i>	Coated aluminum current collector. Positive electrode.
<i>Foil Tabs</i>	The uncoated, notched portions of the electrode which are gathered and welded to the battery tab. Unlike the battery tab, the foil tabs reside inside the pouch.
<i>Battery Tab</i>	The external battery cell lead. For Li-Ion pouch cells, this is often a strip or plate of aluminum or copper for the positive and negative leads, respectively.
<i>Internal weld</i>	Connection between the electrode foil tabs and battery tab. Resides inside the pouch.
<i>Inline</i>	An inspection process is considered “inline” if it can inspect 100% of parts while maintaining necessary throughput. It can be a separate station.
<i>Offline</i>	An inspection process which cannot be performed inline, e.g., would require the manufacturing process to be halted or slowed below required throughput. To meet throughput demands, the inspection must be performed in an audit fashion.
<i>Nondestructive Testing/Evaluation</i>	Inspection technique used to evaluate a part or material for conformance without affecting the serviceability or intended use of the part. Commonly referred to as NDT or NDE.
<i>Quality Verification</i>	Techniques which ensure the quality of each stage of the manufacturing process is within product specifications.
<i>OCV</i>	The voltage across the leads with no load connected to the battery. This provides a measure of the state of charge of the battery and is used in formation and end of line testing.

## APPENDIX B. FUTURE ELECTROCHEMISTRIES

Contained below is a brief list of future electrochemistries discussed in Section 3.

- **Green solvent based chemistries** utilize biosolvents or water [122] and new binders in place of NMP solvents and PVDF binders. They are an emerging area targeting reduced manufacturing cost, process complexity and environmental impact. These benefits are largely a result of eliminating the need for solvent recovery systems for NMP. Additionally green solvents are less toxic than NMP, making them easier for employees to work with safely. Electrode coating to substrate adhesion is a key challenge in these chemistries and is an important topic of research in battery cell manufacturing.
- **Dry electrode processing** eliminates solvent processing issues entirely by using solvent free binders for the intra-coating and coating-substrate bonds. It is a promising manufacturing technology that enables thicker coatings and higher energy density cells at the cost of power density [120]. Similar to green solvents, the dry coating solvent free approach is more environmentally friendly than traditional NMP based solvent slurries and decreases process complexity and manufacturing cost [40,123].
- **Silicon and silicon-oxide anode** active materials promise higher specific capacity [114], a key enabler for longer range vehicles in space constrained automotive applications. However, due to the expansion and pulverization with cycling, these active materials require a prelithiation step prior to assembly. This thin (1–15 µm) layer of lithium metal provides a reservoir to compensate for the lithium consumed as the SEI continues to grow on newly exposed surface area. Adding the complication of working with lithium metal necessitates the manufacturing processes to take place in a dry (dewpoint < -40 °C) or inert atmosphere (Ar, vacuum) due to the chemical reactivity of lithium.
- **Blended cathode** [116,117] or **anode** [118,119] materials are used to balance drawbacks of some materials with benefits of others. One benefit is that a better balance of power and energy density can be achieved with this method. Blending active materials can also result in lower energy release in thermal runaway for cathodes (LCO/NCM) [117] and better cycle life for anodes (Graphite/Si) [118].
- **Lithium metal anodes** [121] are widely considered to be the next generation target chemistry due to lithium’s high specific capacity (1 mAh/cm<sup>2</sup>) is achieved with just 5 µm Li metal vs. 20 µm graphite). This enables significantly thinner anodes (reducing from >100 µm for graphite to <30 µm for lithium metal). A key challenge is the chemical reactivity of lithium which requires the manufacturing processes operate in a dry (dewpoint < -40 °C) or inert atmospheres (Ar, vacuum).

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