Technical Overview

Vacuum and Leak Detection in Roll-to-Roll Metal Deposition

Focus on lithium-ion batteries

Abstract

Roll-to-Roll (R2R) web coating techniques involve continuous processing of flexible substrates, crucial for high-throughput production in industries like packaging, flexible electronics, thin-film solar cells, and lithium batteries. These methods are cost-efficient, scalable, and versatile. Maintaining high vacuum and effective leak detection is essential for preventing contamination and ensuring quality, particularly in lithium battery (LiB) production.

R2R deposition in LiB manufacturing enhances productivity and reduces costs, meeting the growing demand for efficient batteries.

Agilent offers specialized vacuum and leak detection products for R2R processes in LiB production, aiding the automotive industry's shift towards electrification.

Introduction

This technical overview explores the fundamentals of Roll-to-Roll (R2R) techniques, their applications, and the importance of vacuum and leak detection. It highlights the role of R2R deposition in lithium battery (LiB) production, and the critical function of vacuum and leak detection in this context.

What is Roll-to-Roll?

Roll-to-Roll (R2R) web deposition is a manufacturing process where flexible substrates are processed in a continuous manner from one roll to another. This technique is commonly used in the creation of various thin-layer materials and products across multiple industries (Figure 1).

Figure 1. Rolls guiding substrate movement in a Roll-to-Roll vacuum coating machine.

The R2R technique enables high-throughput and cost-effective manufacturing through multiple key steps:

1. Unwinding a substrate from a roll
2. Passing it through various processing stages
3. Rewinding it onto another roll

Where is Roll-to-Roll used?

Roll-to-Roll (R2R) techniques provide a versatile and efficient manufacturing process that drives innovation across multiple industries, including:

- **Electronics and power electronics:** Flexible displays, sensors, and circuits using conductive inks, supercapacitors, and flexible printed circuits in power converters
- **Healthcare:** Medical sensors and wearable health monitoring devices
- **Packaging:** Barrier films to protect food from gases and moisture
- **Textiles and decorative coatings:** Advanced materials for various aesthetic and functional uses
- **Environmental applications:** Filters for water purification and gas separation
- **Automotive and aerospace:** Lightweight, flexible materials (Figure 2)

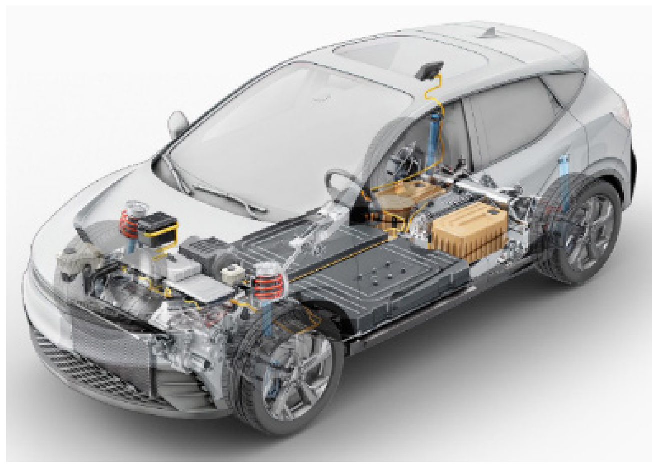


Figure 2. Electric vehicle showcasing all key traction components.

- **Energy:** Thin-film transistors, photovoltaic cells, and lithium batteries (Figure 3)

Figure 3. Close up of a solar panel with photovoltaic cells.

Why are vacuum and leak detection important in Roll-to-Roll techniques?

Vacuum is fundamental to the success of Roll-to-Roll techniques. It ensures the integrity and efficiency of the deposition process, leading to high-quality products and cost-effective production through:

- Reduction of contaminants such as dust, moisture, and other particles that can adversely affect the quality of the deposited films
- Removal of chemical substances that could spark unwanted reactions
- Achievement of uniform deposition of materials across the entire substrate
- Precise control of the deposition parameters, such as temperature, pressure, and material flow, leading to better process repeatability
- Improved adhesion of the deposited material to the substrate

Leak detection is crucial in Roll-to-Roll (R2R) processes, as the presence of leaks can lead to the entrance of foreign substances. This can result in defects in thin films, an increase in system downtime, and the dispersion of materials hazardous to humans and potentially harmful to the environment. From an economic perspective, the downtime of an R2R system due to a leak and the resulting scrapping of a batch of product can be very costly.

Helium leak detection is widely recognized as the most thorough and sensitive technology. Test results are clearly quantified, allowing for the quick pinpointing of the location and relative magnitude of leaks (see Figures 4 and 5).

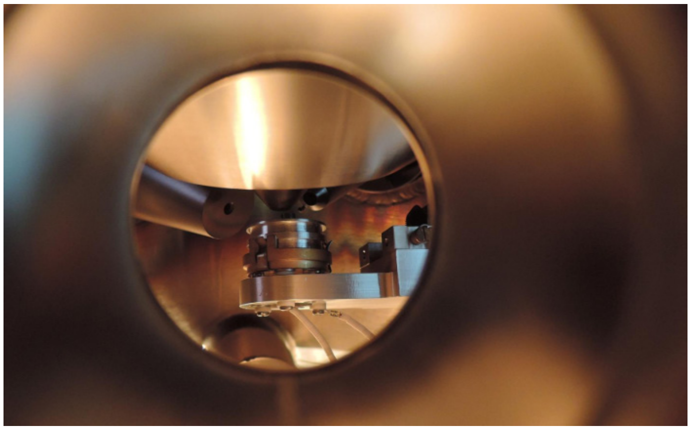


Figure 4. Deposition chamber of a Roll-to-Roll vacuum deposition device.

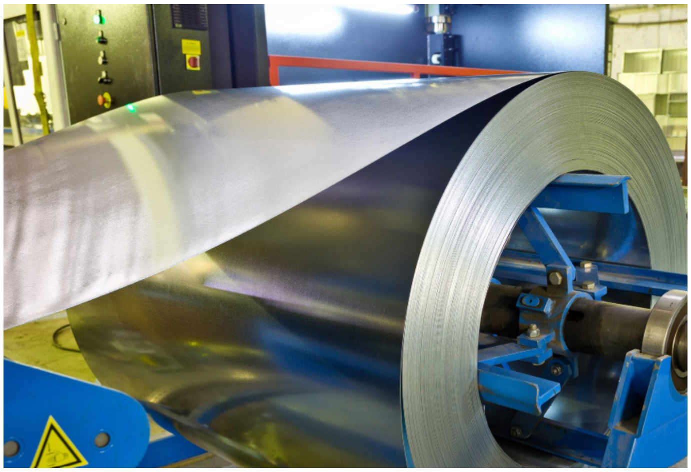


Figure 5. Deposition substrate coil.

Roll-to-Roll deposition for lithium batteries

The adoption of Roll-to-Roll (R2R) web coating technology in lithium-ion battery production has become increasingly critical, fueled by the rapid expansion of electric vehicles (EVs) and the growing demand for high-performance energy storage solutions. The current collector in ion batteries, traditionally made from 4 to 10 µm bulk metal foil, gathers the current produced by the battery. A 1 µm Al/Co film deposited on a polymer film can replace this bulk metal foil, reducing weight and cost while also acting like a fuse (Figure 6).

Figure 6. Set of lithium battery elements.

Why use Roll-to-Roll in lithium battery production?

R2R thin film formation technology has emerged as a viable alternative manufacturing method for lithium-ion battery components, promising advancements in multiple areas, including production speed, process control, and adaptability to different materials and production volumes.

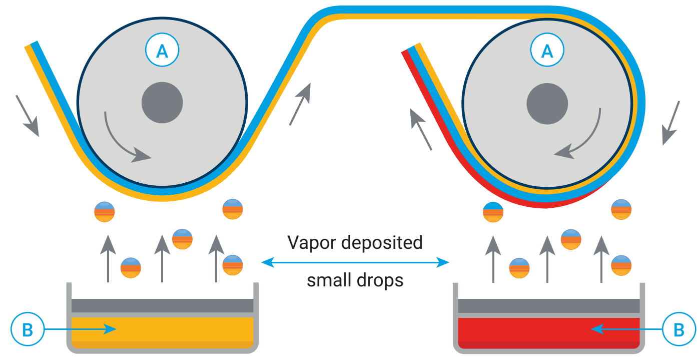
The replacement of massive metal foil in the current collector with a double-sided vapor-deposited polymeric film brings about a paradigm shift in safety, weight reduction, energy density, and environmental impact reduction (Figure 7).

Figure 7. Interior section of a Roll-to-Roll vacuum deposition device.

The role of vacuum and leak detection in Roll-to-Roll for LiB

Maintaining optimal vacuum conditions during Roll-to-Roll deposition and incorporating leak detection processes are pivotal for efficiency and superior product quality.

Ensuring the production of lithium metal foil with low impurities is paramount to preventing the formation of needle-like protrusions known as dendrites. These dendrites pose a serious threat, potentially leading to ignition when reaching the cathode. Maintaining a consistent vacuum level is crucial for preventing contamination and ensuring the uniformity of deposited films. Leak detection is central to this goal, as it allows for the identification and addressing of any potential breaches that could compromise vacuum integrity (Figure 8).



A. Cooled rollers, B. Metals to deposit

Figure 8. Roll-to-Roll technique: principle of operation.

Vacuum and Leak Detection enabling automotive industry electrification

The automotive industry demands higher energy density lithium-ion batteries. Roll-to-Roll deposition technology can produce thinner and more efficient battery components, increasing energy density and reducing weight. It offers faster production, making batteries more affordable and driving the growth of the electric vehicle market (Figure 9).

Figure 9. Electric vehicle at a charging station.

The projected energy density requirements for the automotive industry range between 400 and 600 Wh/kg, and vacuum technology used in Roll-to-Roll deposition techniques concurs in developing current collectors and anodes able to push the battery capacity to that range.

Using vacuum-based deposition techniques as Roll-to-Roll presents an opportunity for the battery market to address four critical areas of expansion in electric vehicle applications:

1. **eVehicle safety improvement:** Safety is improved by suppressing thermal runaway caused by short-circuits in EV batteries.

   With traditional design based on bulk metal current collectors, if a short circuit occurs between the anode and the cathode current collectors due to an object piercing the battery, thermal runaway can result.

   In the same situation, a double-sided deposed current collector with a resin film substrate (such as PET) would act as a fuse, preventing short circuits within batteries.

   The resin film in current collectors will melt before the battery ignites, eliminating contact points with the object that penetrated the battery and stopping the electricity conduction. Double-sided deposited current collectors ensure that short-circuit currents are only temporary, enhancing overall battery and car safety (Figures 10A and 10B).

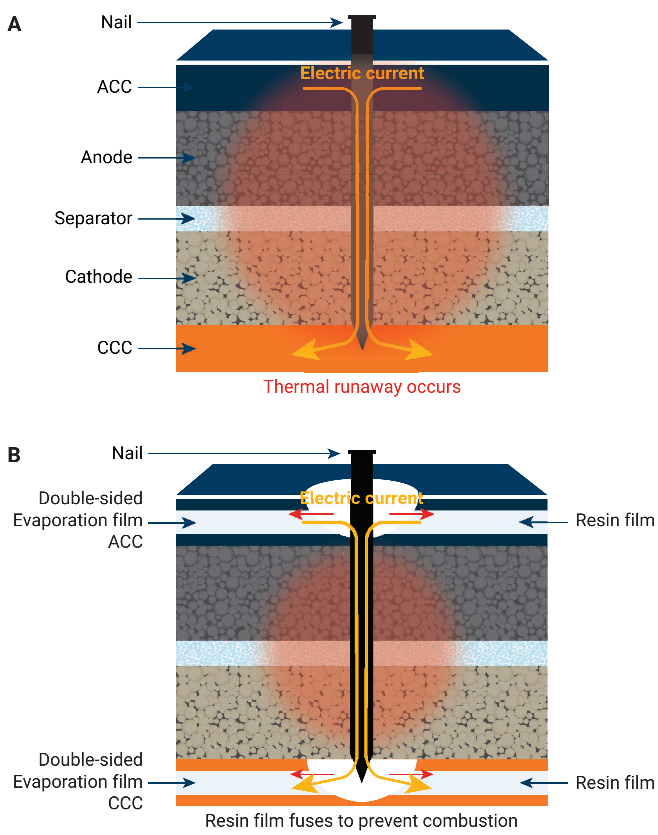


Figure 10. (A) Short circuit in a battery with a metal foil current collector. (B) Short circuit in a battery with a double-sided evaporation current collector.

2. **EV battery pack size and weight reduction:** The resulting increased energy density allows extended driving ranges for electric vehicles (and new possible applications in aviation, such as drones and vertical take-off and landing vehicles) (Figure 11).

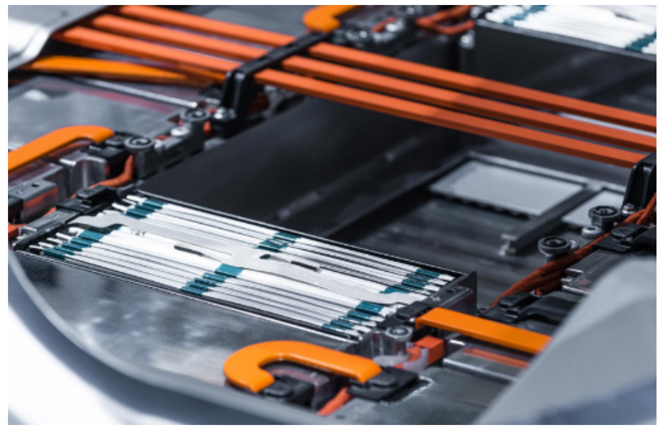


Figure 11. Internal section of electric vehicle battery pack with current connectors.

In conventional lithium batteries, the copper and aluminum foil current collectors account for approximately a quarter of the battery's total weight. However, by replacing these traditional collectors with double-sided evaporation film current collectors, we can achieve significant weight reduction. The weight of anode current collectors and cathode current collectors can be reduced, respectively, by 50 to 60%.

As a result, the overall weight of the battery decreases by approximately 15%, and the energy density – representing the storage capacity per unit weight – increases by approximately 20%. This improvement in energy density translates to an enhanced driving range for electric vehicles.

In summary, adopting double-sided evaporation film current collectors not only reduces weight, but also contributes to more efficient and longer-lasting batteries (Figures 12A and 12B).

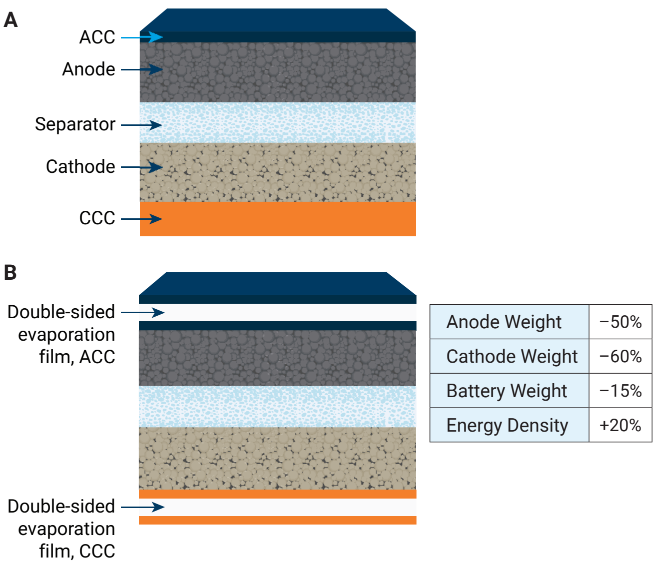


Figure 12. (A) Basic structure of a liquid lithium battery. (B) Basic structure of a lithium battery with a double-sided evaporation film.

3. **Cost reduction:** As batteries account for approximately 40% of an EV's total cost, lowering battery production costs can drive EV adoption (Figure 13).

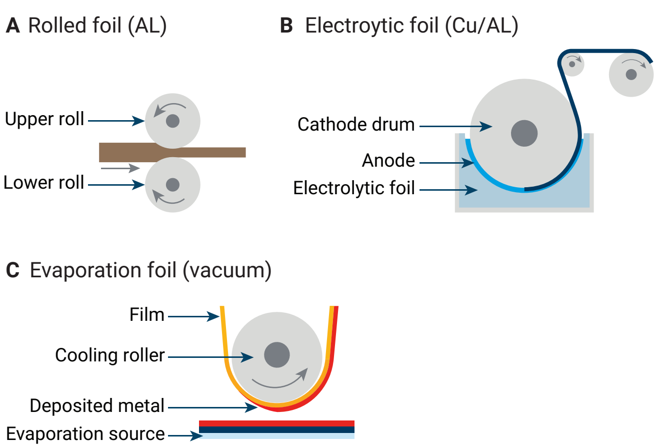


Figure 13. Different types of foils for lithium batteries: (A) rolled foil, (B) electroytic foil, and (C) evaporation foil.

Conventional metal foil current collectors, such as rolled aluminum foil (produced via rolling) and electrolytic copper foil (made through plating), are typically 5 to 10 microns thick, as thicker structures would be difficult to handle.

In contrast, double-sided evaporation current collectors create thin metal films on both sides of a resin film using vacuum evaporation. This process allows for thinner metal layers, minimizing material usage and reducing manufacturing costs.

Table 1. Comparison of thickness and maxumum width for rolling foil, electolytic foil, and vacuum R2R foil.

	Rolling Foil	Electrolytic Foil	Vacuum R2R Foil
Thickness	6 to 100 µm	5 to 140 µm	50 nm to 3 µm
Maximim Width	650 mm	1,300 mm	> 1,660 mm

4. **Greenhouse gas (GHG) emission reduction for vehicles:** Net-zero emissions targets can be achieved by minimizing GHG generation for eVehicles during battery pack manufacturing.

   As the conventional rolling method for foil production consumes substantial electricity, copper and aluminum foils used as current collectors in lithium batteries contribute to one-third of CO_2 emissions from battery manufacturing (Figure 14).

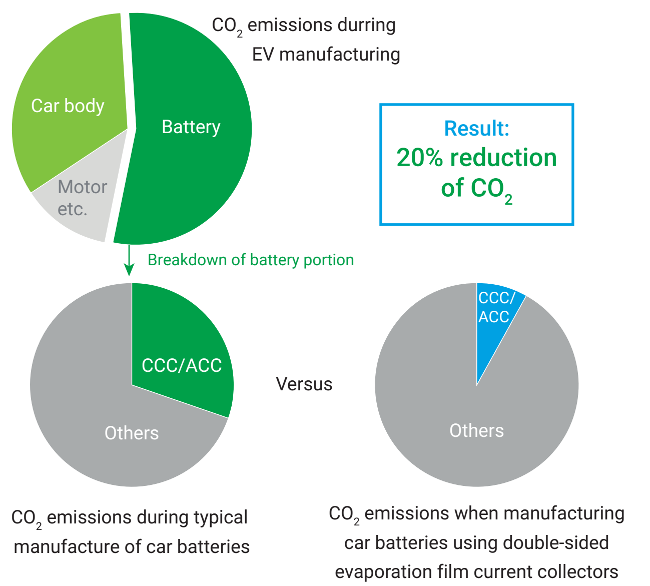


Figure 14. CO_2 emissions from eVehicle and lithium battery production. (Source: based on IEA Global EV outlook 2019).

This is particularly important when considering that half of the CO_2 generated during an EV production process comes from battery production.

Double-sided evaporation current collectors can reduce the required amount of metal material and energy for production. This reduction can contribute to lowering CO_2 emissions from EV production by an estimated rate of 20%.

Frequently asked questions

How does vacuum affect the ease of vaporization in Roll-to-Roll systems?

The degree of vacuum plays a crucial role. The lower the pressure, the easier it is for materials to vaporize. Extremely low pressures, such as those guaranteed by Agilent diffusion pumps in metal deposition systems, promote rapid vaporization at lower temperatures, resulting in significant energy savings during the process (Figure 15).

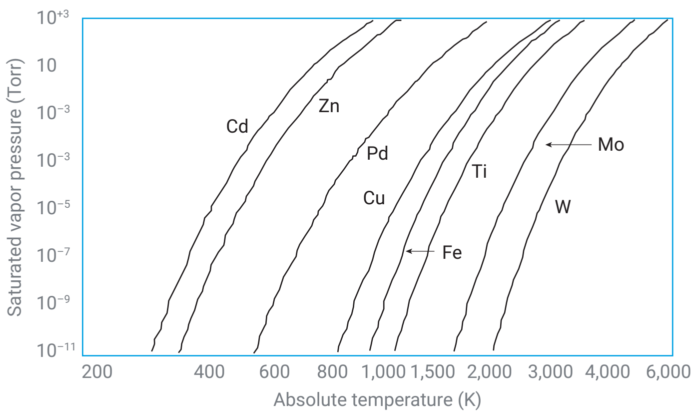


Figure 15. Vaporization rates of different metals at various temperatures.

In a Roll-to-Roll deposition system, the mean free path of evaporated or sputtered atoms is proportional to the vacuum level. It has to be greater than the distance between the coating material and the substrate. Why?

The mean free path of evaporated or sputtered atoms must be greater than the distance between the coating material and the substrate to avoid change of direction caused by collisions with gas molecules. This ensures that the atoms or molecules can travel directly to the substrate without being deflected or losing energy and this is why vacuum is so crucial for a successful deposition (Figure 16).

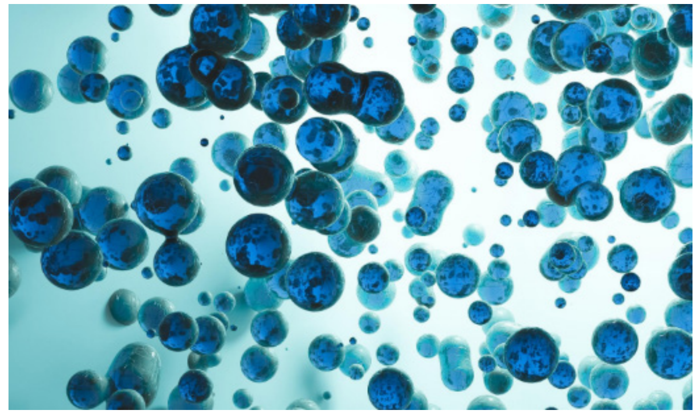


Figure 16. Atoms in vaporized form.

Why does outgassing represent a significant issue during the unwinding of rolled substrates?

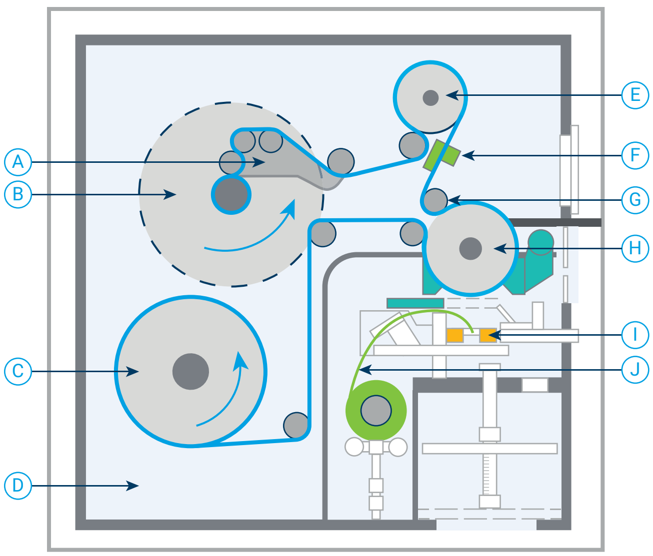
Outgassing is a significant issue during the unwinding of rolled substrates because the large surface area of the rolled substrates results in a huge amount of gas being adsorbed. The gas trapped inside the roll cannot easily escape through the narrow gaps between the layers, leading to significant outgassing when the substrate is unwound. Agilent pumps provide the right pumping capacity to manage the gas load generated by roll unwind during the process.

Figure 17. Technicians monitoring roll unwinding.

What are the typical vacuum requirements in a Roll-to-Roll coater?

In general, two vacuum areas are required in a Roll-to-Roll coater:

- The area where the foil is unwound, and a large quantity of trapped gas is released and pumped out. The pressure is generally in the low vacuum range, from 10^{-1} to 10^{-3} mbar.
- The deposition area, where lower vacuum is required to deposit metal substrate in a clean and optimized environment. The pressure is typically between 10^{-3} and 10^{-6} mbar (Figure 18).



A. Pivot arm
B. Rewind roll
C. Unwind roll
D. Vacuum chamber
E. Tension roller
F. Metrology
G. Guide roller (example)
H. Coating drum
I. Boats
J. Aluminum wire

Figure 18. Main sections of a Roll-to-Roll coater.

Vacuum and leak detection products for LiB Roll-to-Roll

Agilent diffusion vacuum pumps are typically used to evacuate the processing chamber to a pressure between 10^{-3} to 10^{-8} mbar. They offer pumping speeds of up to 50,000 L/s. These pumps are designed to handle high throughput while minimizing oil back-streaming. Their robust design ensures a long service life, prevents contamination, and guarantees the integrity of the deposited materials.

Lower pressures and lower presence of hydrocarbon achieved by Agilent Turbo-V 1K-G and 2K-G pumps are essential for depositing ultrathin films and ensuring the highest levels of purity in atomic layer deposition roll coaters.

Agilent diffusion pumps benefit the Roll-to-Roll process:

- High pump capacity (throughput) enables faster and higher quality deposition
- High pumping speed in the range between 1×10^{-2} mbar, and 1×10^{-3} mbar (crossover pressure)
- Quick pumping down when deposition chamber valves open
- Stable vacuum
- Low oil back stream
- No moving parts and electronic components: Robustness and resistance to dust
- Minimal cooling water requirements and flexibility with cooling water temperature (Figure 19)

Figure 19. Agilent HS-20 diffusion pump.

Agilent turbomolecular pumps benefit the Roll-to-Roll process:

- Dry high vacuum process pump
- Pumping speed from 70 to 2,000 L/s, high gas load
- Reliable, robust, and maintenance free
- Resistant to air in-rush, dust, and process particle
- Rugged integrated IP54 control unit (Figure 20)

Figure 20. Agilent Turbo-V 2K-G pump.

Leak detection systems are also critical for maintaining the integrity of the vacuum environment in Roll-to-Roll web coaters for lithium battery production. Various techniques based on Agilent HLD and C15 leak detectors identify and locate even the smallest leaks, allowing for prompt repairs and maintenance. This contributes to minimizing downtime and improving overall production reliability. Agilent helium leak detectors based on mass spectrometry technology provide accurate, stable, repeatable, and fast leak measurement (see Figures 21 and 22).

Figure 21. Agilent C15 helium leak detector.

Figure 22. Agilent HLD MR15 mobile helium leak detector.

The combination of precise vacuum control and leak detection ensures that Roll-to-Roll deposition processes can produce high-quality coatings with consistent thickness and properties, which are essential for the manufacturing of high-performance lithium-ion batteries (Figure 23).

Figure 23. Agilent Vacuum gauge heads and Agilent XGS-600 controller.

Agilent helium leak detectors benefit the Roll-to-Roll process:

- State-of-the-art helium detectors for accurate and fast leak measurement
- Wet or dry pumping configurations
- Mass spectrometry and permeable membrane technologies
- Ease of use, stable, and repeatable measurement

Conclusion

Roll-to-Roll (R2R) processes revolutionize manufacturing by enabling continuous, high-throughput production of advanced materials. In the context of lithium battery (LiB) production, vacuum pumps and leak detectors play pivotal roles, maintaining optimal vacuum needed to ensure uniform coating thickness and prevent contamination.

Vacuum pumps and leak detectors are indispensable tools, safeguarding quality, safety, and efficiency in R2R processes for LiB production.

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