Modular Lithium-Ion Cell Opening Approaches for an Automated Disassembly and Enhanced Recycling Efficiency

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***Abstract*—The increasing number of lithium-ion batteries currently being introduced to the market in Europe and worldwide raises the question of an efficient recycling approach for the valuable materials contained within. To further facilitate direct recycling approaches, the automated disassembly of batteries down to the electrode level becomes necessary. This research presents a modular approach to the opening and disassembly of pouch cell batteries. The study examines various methods for opening the cell housing and investigates and compares their effectiveness, precision, and impact on the recovered product. By evaluating different techniques, this research aims to identify the most efficient and reliable method to automatically open pouch type battery cells. In the comparison, factors such as the integrity of the recovered materials, the speed of the disassembly process, and the potential for automation will be considered. Once the optimal solution is identified, the research describes and implements the translation of this solution into an automated disassembly station. This involves designing and implementing a system that can open various battery cells consistently and accurately, ensuring that valuable materials are recovered with minimal loss or contamination. The modular nature of the approach allows for flexibility and scalability, making it adaptable to different types of batteries and varying production volumes. Overall, this research contributes to the development of sustainable recycling practices for lithium-ion batteries, addressing the growing need for efficient and environmentally friendly solutions.**

***Keywords*—Pouch Cell, Automation, Recycling, Disassembly**

I. MOTIVATION

The transition to a sustainable economy has significantly increased the demand for lithium-ion batteries (LIBs), especially due to their wide-spread use in electric vehicles or consumer electronics. As a result, the critical sourcing of necessary raw materials such as lithium, cobalt, nickel or graphite has intensified. These materials are not only finite but also subject to substantial geopolitical and supply chain risks, as they are mostly sourced and refined abroad. In response, the European Union has introduced stringent regulations mandating the recycling of battery materials and the use of recycled material during cell production, in order to reduce dependency on imports and enhance circular economy practices [1].

In addition to the ecological advantages, effective recycling can also become an economic success factor. This is due to production scrap rates, which are especially high during the ramp-up phase of battery cell manufacturing. Combined with the high costs of raw materials, this leads to a significant financial strain on manufacturers, directly impacting profitability and even threatening the viability of entire business operations in some cases [2], [3].

Current industrial recycling approaches predominantly rely on pyrometallurgical or hydrometallurgical processes. While effective in processing large quantities of material, these methods necessitate the complete breakdown of battery materials into mineral salts [4]. The following required material resynthesis and precursor production adds to the high energy consumption of these process routes. This is particularly inefficient when dealing with production scrap, that may not have even been activated or that has had only a marginally small lifetime [5].

To address these challenges, direct recycling has emerged as a promising alternative. This approach aims to recover and reuse cell components, such as the cathode active material in their molecular form, thereby eliminating the need for resynthesis and thus reducing processing costs and enhancing the environmental impact. A critical prerequisite for direct recycling is the clean and precise separation of anode and cathode active material, thus mandating a high degree of disassembly. As a first process step when disassembling individual battery cells, the automated opening of the cells is required in

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order to remove cell housing components [6], [7].

II. STATE OF THE ART

The casing of pouch-type LIBs consists predominantly of pouch foil, a multilayer laminate structure that serves as the primary housing material, enclosing the electrode-separator compound (ESC). It serves both mechanical, chemical, and electrical protection functions. Understanding the construction and material properties of this laminate is fundamental for developing suitable cell opening methods.

The foil laminate housing of a typical pouch cell can be manufactured either from a single folded sheet or from two separate sheets of laminate. At least one side of this housing is formed using a deep-drawing process to accommodate the internal stack geometry. The final pouch casing is commonly produced by heat-sealing three sides (in case of a two-piece foil configuration), or all four sides of the battery if two separate sheets of laminate are employed (see Fig. 1 a)). The battery drain tabs are preassembled with Polypropylene (PP) sealing tapes, which are heat-sealed simultaneously with the pouch foil to ensure the tightness and integrity of the casing. To reduce the spatial footprint of the cell, the sealed rims not containing the tabs are often folded and secured to the outside of the cell using tape, as can be seen in Fig. 1 b) and c).

Another differentiation between pouch cell designs can be made by the orientation of their drain tabs, existing either in a counter-tab orientation with the positive and negative tab facing away from each other (Fig. 1 c)), or the same-side orientation with tabs being placed next to each other on the same side of the cell (Fig. 1 a) and b)). Especially for larger geometry pouch cells, also known as blade cells, the counter-tab orientation has gained increasing importance [8], [9].

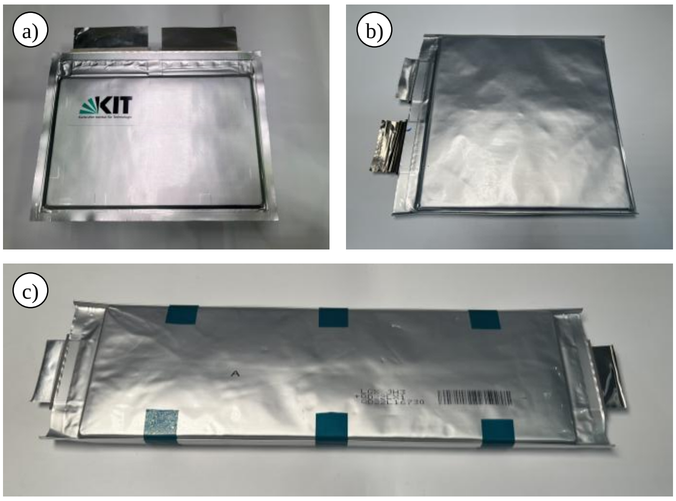

Fig. 1. Different types of Pouch cell assemblies: a) without folded seams, b) with folded seams, c) with folded and taped seams and a countertab setup.

The pouch laminate itself is a multilayer composite (see Fig. 2), typically comprising three to four distinct material layers, each chosen to fulfill specific functional requirements. The total thickness of the pouch foil varies by manufacturer but typically falls within a standard range of 110 to 160 micrometers. The functional layers of the composite include the following [10], [11]:

- The inner layer is made of polypropylene (PP), chosen for its heat-sealing capability at temperatures above approximately 160°C. This layer ensures a basic seal around the cell contents.
- The center layer is typically made from aluminum foil, serving as a barrier layer to shield the inner components from moisture and light.
- The outer layer is usually polyamide (PA), which enhances the cell's resistance to mechanical damage, electrical stress, and chemical exposure.
- Optionally, a layer of polyethylene terephthalate (PET) may be included to improve the isotropic tension distribution, thereby enhancing formability during deep drawing.

The functional layers are bonded using adhesive layers, each optimized for compatibility with adjacent materials:

- Polyolefin (PE)-based adhesives between the PP and aluminium layers as well as the PA and PET layers (if present)
- Polyurethane (PU)-based adhesives between the PA and aluminium layers

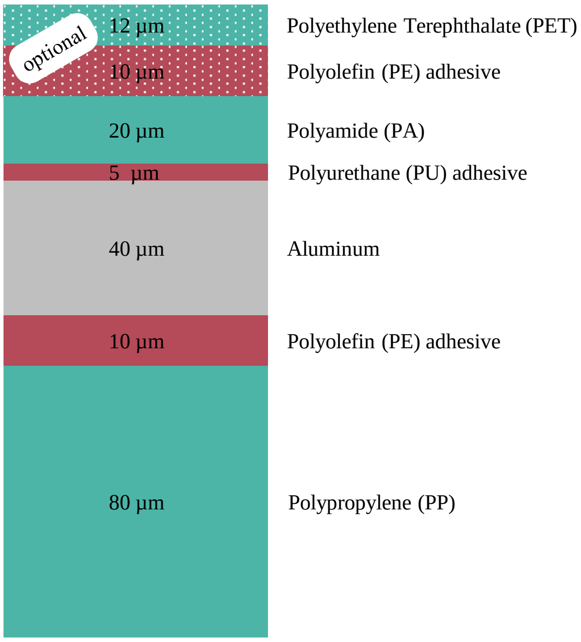

Fig. 2. Layers of pouch foil laminate with typical thicknesses.

Previous research has addressed automated disassembly of pouch-type LIBs with varying degrees of generalization and process integration. Reference [12] developed an automated opening and disassembly station specifically tailored for Z-folded pouch cells, utilizing a shear-cutting fixture. However, the system was constrained to a particular cell model featuring a folded pouch foil with only one side deep drawn, limiting its applicability to broader cell designs. In another study, [13] introduced an opening and disassembly station for Z-folded cells. Their system employed a combination of shear and ultrasonic cutting methods and was theoretically compatible with pouch cells of varying sizes and geometries. Nevertheless, the post-opening condition of the extracted ESC remains unreported, and it is unclear whether the internal stack was fully preserved without mechanical damage, possibly introduced by the ultrasonic knife during the cutting process.

III. APPROACH

The development of a modular, automated cell-opening method for pouch-type LIBs described in this paper was guided by a structured and requirement-driven approach. The overall goal was to establish a process capable of handling a wide variety of LIB formats while ensuring compatibility with downstream recycling steps.

A foundational step was the identification and structuring of technical and functional requirements. Given the significant variation in pouch cell geometries and sizes across manufacturers and applications, a key requirement was the ability to process a wide range of LIB shapes and sizes while still achieving a high throughput. Additionally, the method had to avoid contamination of the ESC and minimize thermal and mechanical stress on internal components during cutting. These factors are crucial to preserve material integrity for high-quality recycling outcomes.

In order to identify suitable separation methods, a comprehensive analysis of cutting technologies based on DIN 8580, which classifies manufacturing processes, was conducted. The focus was placed on identifying techniques capable of separating pouch foil without inducing high temperatures, mechanical deformation, or introducing contamination.

Further, a utility analysis was conducted to evaluate the identified cutting methods against the defined requirements. This analysis concluded that only processes from the separation category are suitable. These include shear cutting and ultrasonic cutting, both of which meet the critical performance thresholds. Shear cutting should offer a cost-effective solution with a relatively simple mechanical integration, while ultrasonic cutting should provide high-precision capabilities and clean separation of the pouch foil.

To verify the practical suitability of the selected methods, a series of experiments was performed. These experiments focused on evaluating the suitability of both cutting processes for cleanly opening pouch-type LIBs while minimizing thermal stress and mechanical influences on the ESC. Specifically, the ultrasonic cutting system was evaluated for its ability to reliably cut through all relevant pouch cell material combinations, including pouch foil sealing seams as well as aluminum and copper drain tabs. Additionally, shear cutting experiments were conducted to examine the influence of different material combinations on the required cutting forces. These tests formed the basis for the mechanical design of cutting tools and the expected operational limits of the system. Based on the validated cutting principles, the process was transferred into a complete automated system design.

IV. EXPERIMENTAL

The experimental configurations, materials, and measured parameters were chosen to reflect realistic conditions in an automated disassembly environment. The samples for both cutting methods were constructed by manually assembling pouch cell dummies using 2 sheets of *D-EL408PH(3)* pouch foil with a total thickness of 153 micrometers per sheet by *Dai Nippon Printing Co., Ltd. (DNP)* of Japan. As drain tabs, both aluminum and copper tabs with a thickness of 200 micrometers were used. All tabs were equipped with a 100 micrometer PP sealing tape on each side, for a total thickness of 400 micrometers within the sealing section. The heat-sealing seams between the different components were achieved using five kilowatt sealing bars set to 170 degrees centigrade and applied for five seconds per seam.

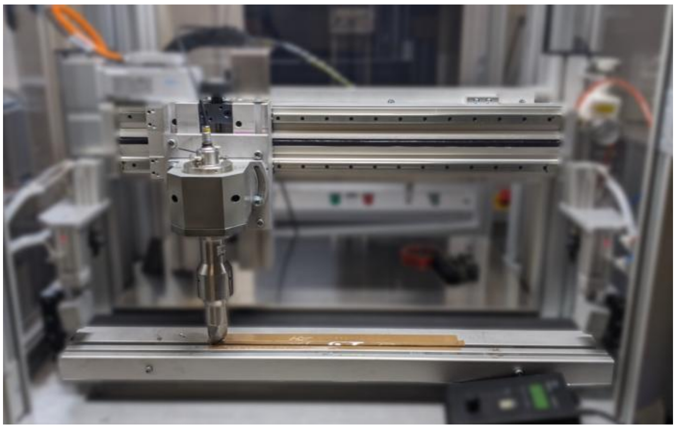

Fig. 3. Test stand for ultrasonic cutting experiments.

The ultrasonic cutting experiments were conducted using a 2000 Watt ultrasound generator *Sonic Digital HS3* by *Weber Ultrasonics*. The ultrasonic converter and sonotrode were mounted on a linear axis, as can be seen in Fig. 3 and equipped with a carbide cutting knife, allowing it to be moved precisely along a guided path. The samples were mounted on a surface above a groove, which allowed the knife to fully pass through the material. The ultrasonic system operated at a frequency of 20 kilohertz. Tests were carried out at varying cutting speeds ranging from 150 to 600 millimeters per second to investigate the influence of process velocity on cutting quality and consistency. Each test was performed both with ultrasonic excitation enabled and disabled, allowing the isolation of the ultrasonic effect on cutting performance.

Additionally, a second set of experiments focused on characterizing the force requirements for shear cutting. For this purpose, an articulated robot *Kuka KR4-R600* was used to press a cutting blade downward into the test samples (see Fig. 4). During each cut, the applied force was continuously measured by a six-axis force-torque sensor *ForTTran SG 500-20* to determine the mechanical resistance of different material combinations. The objective of this experiment was to evaluate how the presence of different cell components, particularly metal tabs and sealing layers, influenced the cutting force.

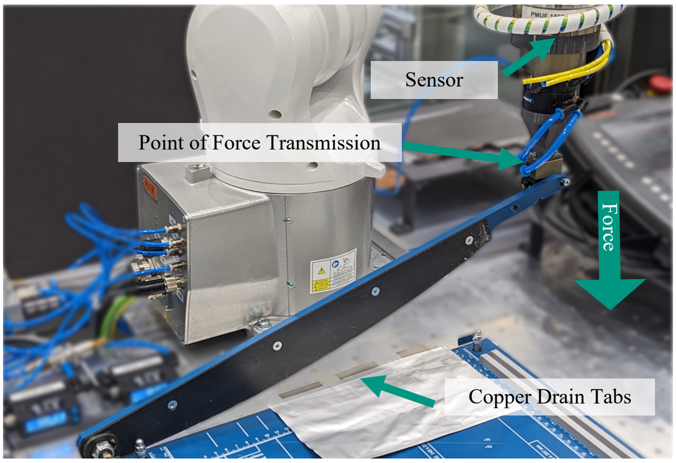

Fig. 4. Test stand for shear cutting force measurement experiments.

V. RESULTS

The experimental investigations yielded clear insights into the performance characteristics and limitations of both ultrasonic and shear cutting methods for pouch cell opening. In the case of ultrasonic cutting, the activation of the ultrasonic excitation significantly improved the succes rate of material penetration and cut quality. Across the tested speed range of 150 to 600 millimeters per second, no significant influence of cutting speed on the quality of the cut was observed. Ultrasonic cutting did not cause a significant heat buildup on the blade or within the cutting zone of the material, enabling the removal of sealed pouch edges without influencing the ESC.

However, the tests also revealed a clear limitation: ultrasonic cutting was not suited for cutting through the copper drain tabs. The tab material was too thick and mechanically resistant, exceeding the capability of the ultrasonic knife. In addition, when cutting aluminum tabs, significant wear on the face of the blade could be observed after only five cuts, as can be seen in Fig. 5. While the aluminum abrasion collected on the knife did not immediately influence the cutting result, the wear leads to a substantial reduction in the knives performance, increasing necessary cutting forces and eventually leading to a breakage of the carbide blade.

The shear cutting experiments yielded valuable data, particularly on the force requirements for the various material combinations. The exemplary force measurement graph for cutting three distinct copper tabs (Fig. 6) shows a distinct increase in load when cutting copper tabs compared to the pouch foil seams alone. This confirms the expected rise in resistance due to the higher material thickness and ductility of the metal components. Furthermore, the graph illustrates a characteristic increase in applied force as the cutter progresses further into the seam, indicating reduced leverage.

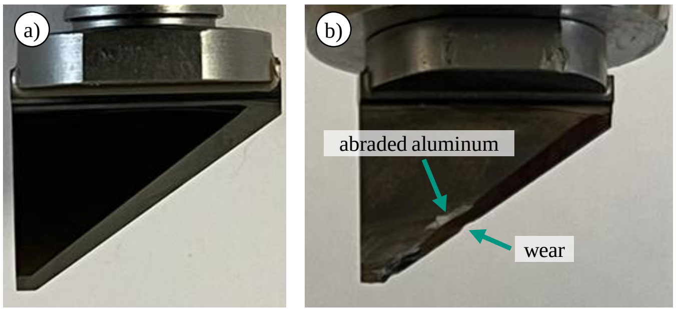

Fig. 5. Comparison of: a) an unused carbide, ultrasonic knife and b) the knife used for the experiments.

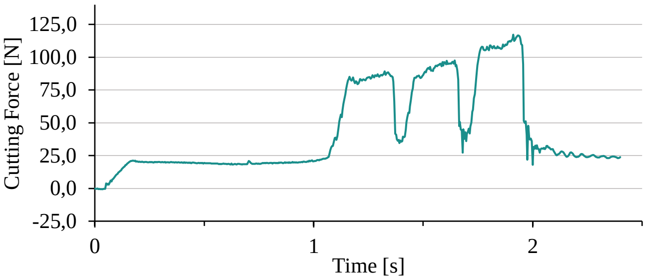

Fig. 6. Force required for sheer cutting a test piece with three drain tabs.

Together, these results demonstrate the relative strengths and constraints of each method. Ultrasonic cutting offers high precision and cleanliness for foil-based seals but is unsuitable for metallic tab sections. In contrast, shear cutting provides a robust mechanical solution capable of cutting through both foil and tab materials. These findings directly inform the design trade-offs for an adaptable cell-opening system aimed at maximizing efficiency while preserving material integrity.

The direct comparison of pouch cells being opened using an implemented prototype shear cutting mechanism and the ultrasonic cutter are shown in Fig. 7. Both methods successfully removed the sealed edge entirely without making contact with or damaging the ESC. Notably, the ultrasonic cutter was able to cut closer to the cell stack than the shear mechanism, owing to its knife-based design rather than a shear-cutting approach. However, the shear mechanism still achieved complete removal of the seal, demonstrating its adequacy for the task. This was made possible by the implementation of a prototype setup, using a lower knife being only 1 millimeter thick, which enables cutting close to orthogonal surfaces, such as the deep drawn section of the pouch foil. Nevertheless, for successful operation, this method requires the battery cell to be positioned with high precision within the shear cutting mechanism.

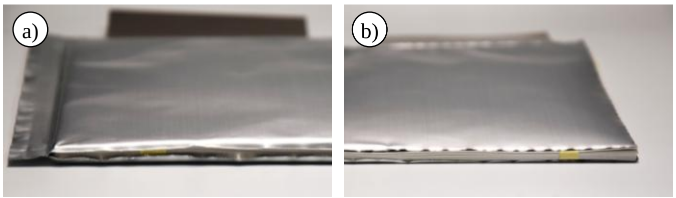

Fig. 7. Pouch cell cut open on: a) the shear and b) the ultrasonic cutting test stand.

VI. DISCUSSION AND OUTLOOK

Based upon the results presented above, the shear cutting operation has been selected as the preferred method for the opening of pouch cells. This is especially due to the capability to successfully open all relevant sides of the pouch cell, even with the presence of drain tabs. Further advantages include the robustness of the process as well as the low cycle time (currently 27 seconds for the entire cell-opening process). The stated requirements concerning integrity of the ESC as well as the prevention of possible thermal effects could be met as well.

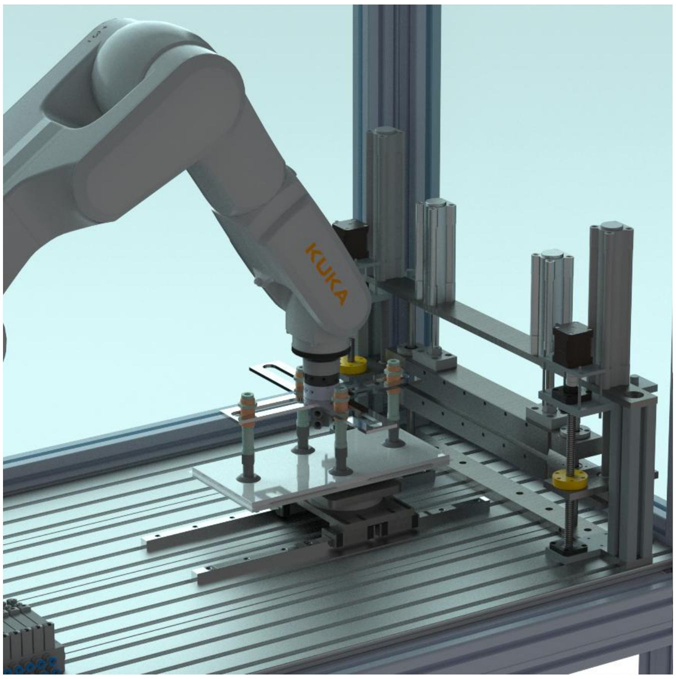

Fig. 8. Final design of the disassembly station with guillotine cutting mechanism.

The final design (see Fig. 8) for the modular cell opening station consists of a handling unit capable of positioning all four sealed edges of a pouch cell within the cutting mechanism, as well as the cutting mechanism itself. This modular setup ensures the opening process remains adaptable (also to further cell types) while maintaining the precision and reproducibility essential for downstream recycling and material recovery. The cutting mechanism employs a guillotine shear cut and is designed to operate in close proximity to the ESC, enabling the complete removal of sealed edges. A *Kuka KR 6 R 900-2* robot equipped with a vacuum gripper is used for handling the pouch cell. After grasping the cell, the robot places it on a positioning table, capable of linear movement and rotation around its center. By applying pressure, the robot moves the battery together with the table using friction forces. The robot then positions the LIB into the shear cutting mechanism, activates the cutter, retracts the cell, rotates it by 90 degrees, and repeats the process until all sealed edges are cut. Subsequently, the robot can lift the upper pouch foil, the ESC, and the lower pouch foil successively from the platform.

For future works, the described setup will be implemented and expanded using a vision system, in order to automatically detect the orientation and size of incoming pouch cells. As a further step, the dismantling of the retrieved ESC will be analyzed and automated, in order to present a fully modular disassembly setup, capable of extracting individual electrode sheets from end-of-life or production scrap battery cells.

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