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Battery recycling – Exploitation of laser technologies for dismantling and recycling processes

Max Rettenmeier[a,*], Mauritz Möller[a] , Oliver Bocksrocker[a], Vinayakrajr Salvarrajan[a], Christoph Neugebauer[a]

[a] *TRUMPF Laser- und Systemtechnik GmbH, Johannes-Maus-Straße 2, 71254 Ditzingen*

Abstract

The ramp-up of new production infrastructure to manufacture lithium-ion batteries for battery electric vehicles is moving ahead at a rapid pace. These enormous quantities of vehicle batteries must be recycled in a fast loop due to the increasing shortage of critical raw materials. Laser technologies offer the possibility to perform many of the necessary process steps of dismantling and recycling. In this paper, an application overview and analysis of laser technologies in the field of cutting and ablating processes will be presented. The cutting processes are primarily focused on the dismantling of metal and metal-plastic components of battery packs. Furthermore, in the ablative processes, the ablation of active material of the battery electrode foil using ns-pulsed lasers is investigated. Within the scope of this application, the elaboration of laser-technological parameter fields will be pursued in particular.

Keywords: Recycling; cutting processes, ablating processes, dismantling, battery pack

1. Introduction

1.1. Relevance of battery pack recycling

The increasing global demand for electric vehicles (EVs) has led to a surge in the production and use of lithium-ion batteries, which are the primary power source for these vehicles. While EVs offer numerous environmental benefits compared to traditional internal combustion engine vehicles, the growing number of lithium-ion batteries poses significant challenges for waste management and recycling. As the adoption of electric vehicles continues to rise, there is a pressing need to develop efficient and sustainable recycling methods for lithium-ion batteries to minimize their environmental impact and maximize resource utilization (Duan et al., 2022).

In the realm of end-of-life lithium-ion battery recycling, regulatory measures emerge as a pivotal facet. A key agenda item in the European Union (EU) is the ongoing discussion on the proposed Battery Directive 2019/1020, which aims to replace the previous Directive 2006/66/EC. According to Neumann et al. (2022), this forthcoming regulation will introduce significant requirements for the management of spent lithium-ion batteries. These rules include mandatory requirements such as recycling quotas and labelling obligations for battery manufacturers. With this comprehensive regulatory framework in place, the recycling of spent lithium-ion batteries will gain momentum across Europe in the coming years. Manufacturers are taking responsibility for the batteries they put on the market, while relying on recycling processes to source recycled materials for their operations. Compared to Europe, the US currently lacks comparable initiatives for recycling end-of-life lithium-ion batteries. In contrast, China has already implemented advanced regulations in this area. Key elements of the Chinese regulation include encouraging manufacturers to design batteries that are easy to disassemble, requiring the provision of technical information, promoting second-life applications, and placing responsibility on EV and battery manufacturers. (Neumann et al., 2022)

This shows that the issue of efficient and sustainable battery recycling will grow in importance, not only because of sustainability concerns, but also because of regulatory efforts. It is therefore crucial to develop economically viable technological concepts at an early stage to enable the processing and recycling of the expected volumes of end-of-life batteries.

1.2. Battery Re-X process

Traction batteries for electric vehicles are nowadays usually described as end-of-life at a so-called state-of-health (SOH) of 80% (Podias et al., 2018). This is the point at which most traction batteries for battery electric vehicles (BEVs) are expected to be recycled. A typical process is shown in Fig. 1. Here it can be seen that the

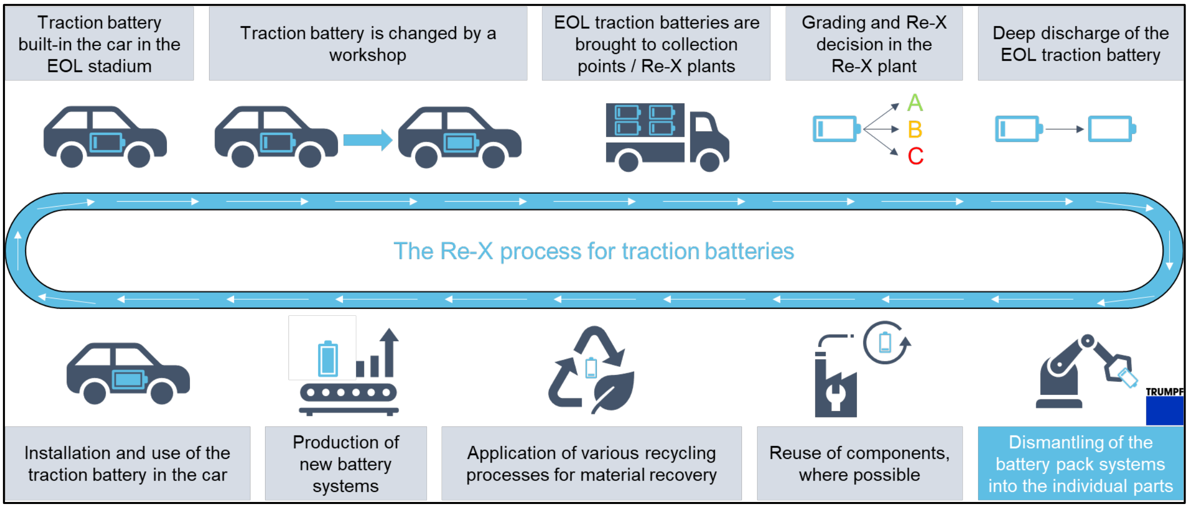

Fig. 1 Process overview battery recycling for traction batteries (own illustration)

dismantling of the battery pack is the first mechanical disassembly step before any further chemical or mechanical recycling or remanufacturing steps can follow. This shows that reliable and cost-efficient dismantling is important for the entire EV battery recycling chain.

In addition to the dismantling process, the ablation of active material from an electrode foil will also be investigated in this paper. As shown in Fig. 2, the active material is removed from the electrode foil. This process can be used, for example, in production scrap recycling.

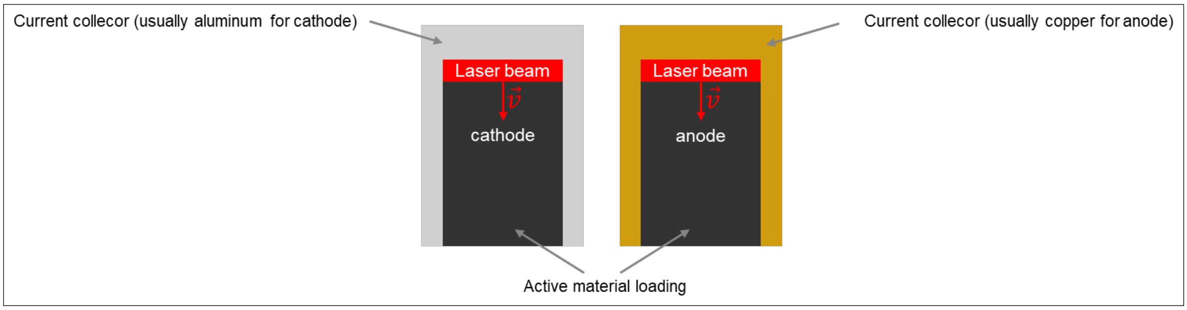

Fig. 2 Schematic illustration of the laser ablation process (own illustration)

2. Methodology and research focus

The first step of this paper is to assess the state of the art. Therefore, an overview of the relevant literature will be made. This will be done separately for the areas of "dismantling" and "ablation". In particular, it will be determined to what extent the application of laser technology in these two areas has already been researched. It will also identify the technological challenges for the current technological approaches in dismantling and ablation. In the further course of this paper, the applications will only be abbreviated as "Dismantling" and "Ablation".

In the second step, gaps in the literature will be identified, especially with regard to the use of lasers. These gaps in the literature will be used to identify where there is a need for further research into laser-based processes.

In the next step, selected research gaps will be addressed through a dual approach. In the area of disassembly, process analogies from related processes will be used to determine whether the use of a laser is possible in principle. In the area of ablation of active materials, actual experimental data will be used to give a first indication of feasibility.

Finally, recommendations for further research will be given based on the findings of the previous steps.

3. State of the art

3.1. Literature overview

To identify relevant literature on the topic of battery pack dismantling, the following search string was entered into the Google Scholar search engine:

(Disassembly OR Dismantling) AND ("Battery Pack" OR "Battery Module")

By incorporating the synonyms "Disassembly" and "Dismantling", it ensures that all relevant search results are captured. The AND conjunction with the battery-related terms ensures that only results from the battery field are displayed. The terms "Battery Pack" and "Battery Module" were used since they are often used as synonyms. Although smaller units with-in a pack are sometimes referred to as modules, there is no consistent terminology in the literature. Therefore, both terms were included to account for variations in usage. The Google Scholar search for “Dismantling”, which was carried out on 11.06.2023, yielded a total of 4,110 results.

Of these, the first 100 search results were examined. A precise detailing of the literature found here can be found in Appendix A. Here the literature is categorized according to relevance and broken down by content. Within the framework of the literature analysis, a focus was placed on the technological challenges. The main aim was to highlight the problems that current technological approaches bring with them. The contents of the literature found and the technological challenges identified are summarized in the following.

A challenge that has been recognized by many authors is the wide design variety of battery packs. This makes a standardized disassembly strategy difficult to implement. Above all, the automation capability suffers from the diversity of variants. This calls for a very flexible dismantling system that can also fulfil the economic requirements despite this. (Baazouzi et al., 2021; Blankemeyer et al., 2021; Fleischer et al., 2021; Gerlitz et al., 2021; Lander et al., 2023; Rosenberg et al., 2022; Wu et al., 2023; Xiao et al., 2023; Zang and Wang, 2022)

A more specific challenge that has also been identified by some authors is screw connections. For example, challenges are that these also have a large variety, requiring frequent tool changes, which makes the disassembly process inefficient. Furthermore, loosening the screws is also a challenge due to wedging and sticking. (Lander et al., 2023; Li et al., 2023; Rastegarpanah et al., 2021; Rosenberg et al., 2022; Xu et al., 2022; Zubaidi and Koneliussen, 2022)

A challenge resulting from the high variety of pack designs as well as the screw problem is the high time effort required for disassembly. This high time input makes the process step of dismantling very expensive. Various strategies are used here to increase efficiency, but these usually work for one single pack architecture and cannot be flexibly applied and adapted. (Lander et al., 2023; Xiao et al., 2023; Zang and Wang, 2022)

In addition, safety challenges, especially in manual disassembly, has been identified. This results in the conflict of objectives that great flexibility is required, but at the same time manual disassembly is associated with inefficiency, costs and safety problems. (Schäfer et al., 2020; Zhou et al., 2021)

In addition to these challenges for the dismantling of traction batteries, the use of irreversible connection technologies was identified as a further core challenge. Here, only Kampker et al. (2021) had the idea of using a laser to cut the busbar connections. Kampker et al. (2021) was the only publication in the considered literature that took laser technology in dismantling operations into account.

To identify the relevant literature on the ablation of active material from electrode foils for the recycling of lithium-ion batteries, the following search string was entered into Google Scholar:

(ablation OR removal) AND (anode OR cathode OR electrode) AND battery AND (recycling OR remanufacturing)

Given that ablation and removal processes are also commonly used in other industries and applications, a strong specification within the search string was necessary. In the initial step, it was specified that anodes, cathodes, or electrodes should be subjected to ablation. To ensure that the results are battery-related, the word "battery" has been added. Additionally, the terms "remanufacturing" and "recycling" were considered as only ablation processes will be investigated in this topic area. In total, the Google Scholar search for "ablation", which was performed on 11.06.2023, yielded 33,700 results. Of these, the first 100 search results were examined. A precise literature review can be found in Appendix B. The literature was categorized and analyzed in terms of content. The main focus was on the analysis of the advantages and disadvantages of different (mechanical) ablation technologies. A summary of the technology landscape for the mechanical removal of active materials from the electrode foil of battery cells as well as the respective advantages and disadvantages is presented hereafter.

It should be noted that the majority of the search results was dedicated to chemical-based methods and processes for the removal of active materials. A helpful overview of the advantages and disadvantages of the various chemical and mechanical processes is provided by He et al. (2021) and Natarajan et al. (2022) (see Appendix B.).

He et al. (2015) and Natarajan et al. (2022) mentioned ultrasound ablation as a mechanical ablation method. A good peel-off efficiency was observed here (He et al., 2015). Furthermore, no or little solvent has to be used and the emissions of the process are low (Natarajan et al., 2022). Unfortunately, ultrasonic ablation has high noise emissions, high energy consumption and poor scalability (Natarajan et al., 2022).

Some papers actually deal with laser-based ablation. However, only the ablation of the SEI is considered here, which is not comparable to the ablation of the entire active material (Liu et al., 2016; Ramoni et al., 2017).

3.2. Research gaps

For the area of "Dismantling" especially the use of laser technology in the dismantling steps is only very rarely discussed. Only Kampker et al. (2021) discuss the use of lasers for the busbar separation. However, a holistic view of laser applications in this area is missing here. Furthermore, a combination of the many problem areas is not sufficiently addressed. The high costs, little flexibility and high time input as well as low degree of automation are often discussed. The solution to one of these points is often addressed separately. However, the holistic approach that can unite all these aspects is also missing here. In summary, on the one hand, the use of the laser should be evaluated and on the other hand, it should be examined in detail to what extent advantages in terms of costs, speed, flexibility and automation can be achieved in combination.

For the field of "ablation", it can be stated that laser-based ablation of active material has not yet been investigated by any publication found. Although Liu et al. (2016) and Ramoni et al. (2017) have investigated the feasibility of laser ablation of the SEI, the entire active material was not considered here either, which is why there is a research gap with regard to this. Therefore, the first step should be to examine the extent to which laser-based ablation processes are applicable here at all and what results can be achieved here. Later, these process approaches must then benchmark themselves against the known chemical and mechanical removal processes.

4. Results and discussion

As explained in Chapter 2, the investigation of laser technology in dismantling is carried out using process analogies. Laser cutting processes have been used successfully in various industries for decades. For example, hot formed parts in the automotive industry are cut reliably and efficiently by laser cutting. Here, for example, 3D laser cutting is also a frequently used technology. Due to the complex and diversified geometries, 3D laser cutting is usually superior to other processes. In this way, different geometries can be cut flexibly at high speed. These process characteristics are analogous to the mechanical disassembly steps for battery packs. Here, too, different and sometimes complex geometries have to be cut quickly and reliably. With regard to the battery pack, there is a particular similarity when cutting the structural elements of the battery pack. For example, when removing the tray cover or the crash and mounting structure as well as the thermo-management. The materials are also often aluminum or steel alloys, which is why there is also an analogy here. But there are also differences between the processes. For example, the hot formed parts are often significantly thinner than the battery pack components. Here, however, it can be seen in Fig. 3 that although the speed decreases with increasing thickness, cuts up to 8mm are possible with standard laser cutting equipment. Most of the structuring elements of the battery pack have a smaller thickness, which is why the use of laser cutting processes for the dismantling of traction batteries appears to be possible in principle from a process perspective. However, there are also various challenges to be mentioned here. For example, in contrast to hot formed parts, it is not pure metal that is cut here, but often other materials such as plastics in the form of seals or adhesives. In addition, with hot formed parts there is no hazardous component under the cutting zone. In the case of an EOL battery pack, however, there are potentially dangerous battery cells in the immediate surroundings of the cutting zone, which requires a precisely planned cutting process. In summary, based on the analogy, it seems possible to use 3D laser cutting processes for the disassembly of structural elements of the battery pack of traction batteries. Here, further research should develop and validate appropriate application approaches.

The second application to be investigated is the laser-based ablation of active material from electrode foils. For this purpose, tests were carried out to determine the basic feasibility of this application. A nano-pulsed laser (TruPulse5020nano) was used. An NMC and an LFP cathode foil were ablated with it. Since the cathode materials are much more valuable and ablation is probably more sensible here, at least from an economic

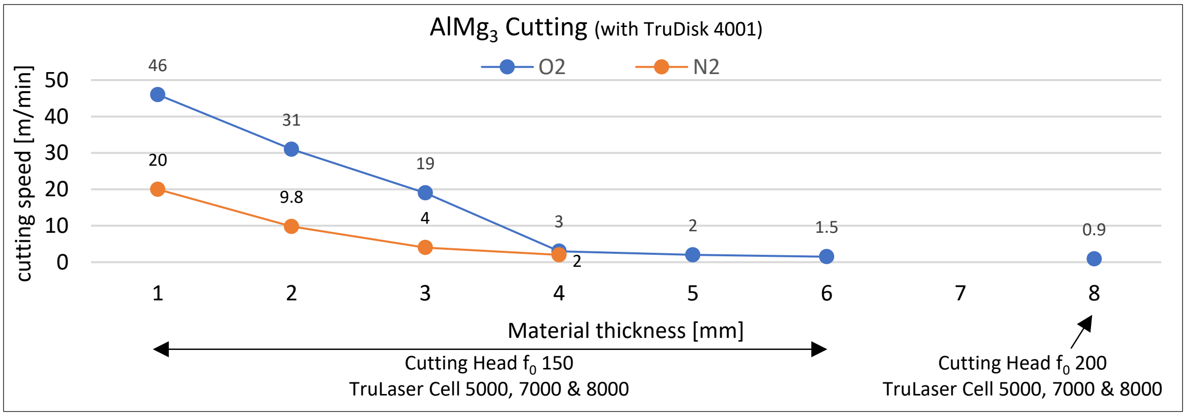

Fig. 3 Laser cutting of $AlMg_3$ up to 8mm with N_2 and O_2 in a comparison of cutting speeds

point of view, this focus was chosen. The tests carried out were only intended to sound out the basic feasibility of the application, which is why the investigations are of a more fundamental nature. The two main KPIs used were the weight difference and the processing time. The weight difference of the foil before and after ablation made it possible to determine to what extent the ablation process was successful, since the loading of the cathode foil was known. The process time clearly shows the speed class of the ablation process in these first trials. In addition, the extent to which the aluminum foil was damaged or burnt was evaluated. This was done by qualitative human visual inspection.

The process parameters and results are listed in Appendix C. (LFP foil) and Appendix D. (NMC foil). The most important results are briefly broken down and explained hereafter.

For the LFP foils in it can be seen that a pulse duration of 10ns produced the best ablation result. The ablation speed was between 1.59-1.75 cm^2/s. For the NMC foils a pulse duration of 10ns also produced the best ablation result in the small test series. Here, speeds between 2.98-3.55 cm^2/s were possible.

Although the ablation results were only assessed qualitatively by human visual inspection, these results give a first indication that ablation of active material of the cathode foils (LFP and NMC) seems possible with nano-pulsed lasers. Further investigations must now be carried out in more extensive test series in order to further validate and explore the application.

5. Conclusion and outlook

The increasing global demand for electric vehicles (EVs) and the subsequent surge in lithium-ion battery production have highlighted the need for efficient and sustainable battery pack recycling methods. This paper has focused on two key aspects: battery pack disassembly and the removal of active material from electrode films. The literature review revealed several challenges in these areas, such as the wide variety of battery pack designs, screwed connections, high time requirements, and safety concerns. In addition, there has been very little research into the use of laser technology in these processes.

In the area of battery pack disassembly, the potential application of laser technology has been discussed through process analogies. 3D Laser cutting techniques have been successfully applied in various industries, demonstrating their process reliability and efficiency. The analogy between laser cutting of complex geometries in other industries and the mechanical disassembly steps for battery packs suggests that laser-based approaches could offer advantages in terms of speed, flexibility, and process stability. However, challenges specific to battery packs, such as the presence of hazardous battery cells in the cutting zone and the presence of additional materials such as plastics and adhesives, must be carefully addressed in future investigations. Further research is needed to assess the technical feasibility and potential benefits of laser-based disassembly processes for traction batteries. This includes developing a comprehensive understanding of safety considerations and optimizing the cutting process for battery pack components.

Regarding the ablation of active material from electrode films, it is worth noting that the literature focuses primarily on chemical-based methods, with limited exploration of laser-based approaches. While some studies have investigated laser ablation of the solid electrolyte interface (SEI), there is a research gap regarding laser-based ablation of the entire active material. The experimental data presented in this paper give an indication that a laser-based ablation process could work. Future research should explore the potential of laser-based ablation processes for removing active materials from electrode films and compare their performance with existing chemical removal methods. In particular, the assessment of the quality of the ablated active material should be evaluated in further studies.

In conclusion, this paper highlights the importance of developing efficient and sustainable recycling methods for lithium-ion batteries. The potential application of laser technology in battery pack disassembly and ablation of active material from electrode films presents avenues for future research and development.

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Appendix A. Literature overview “Dismantling”

Source(s) alphabetical	Focus	Technological challenges and critical factors
Baazouzi et al. (2021)	Investigation of different disassembly strategies	Wide range of battery system designs, Short innovation cycles make Changes in future designs unpreventable
Blankemeyer et al. (2021)	Investigation of automation potential for battery pack dismantling	Current battery pack designs are not made for disassembly operations, Large variety and complexity
Fleischer et al. (2021)	Conceptualization of a flexible disassembly system	High variety of battery pack designs
Gerlitz et al. (2021)	Analysis of challenges for agile and automated disassembly due to large product variety	Product-related challenges: Battery cell type, Type of cell contacting (irreversible), Cell fixation (irreversible), High amount of individual parts for module housing

		Process-related challenges: Localization of non-detachable joints, Battery hazards
Kampker et al. (2021)	Overview about a potential battery remanufacturing process	Laser-based cutting can be very dangerous if cells are damaged while performing the cutting process
Kay (2019); Larsen (2021)	Excluded – no access	
Lander et al. (2023)	Impact of battery pack design on disassembly costs	Fasteners are one of the main challenges for dismantling, Welded parts are also challenging for current dismantling systems
Li et al. (2023); Rastegarpanah et al. (2021); Zubaidi and Koneliussen (2022)	Battery pack dismantling with focus on screw treatment	Screw position and type not publicly available, Performance of screw detection can be improved via eye-in-hand methods, Unfastening due to unknown condition of screws very challenging, size and shape of the screw or nut might change over time (due to friction, force, and temperature),
Mannuß et al. (2020)	Systematic risk assessment for dismantling operations	Every process step of dismantling has its own risk structure
Rallo et al. (2022)	Analysis of local battery dismantling center distributions	High logistics costs for transporting hazardous batteries, Decentralized dismantling hubs are recommended, This allows little scaling and requires a high degree of plant flexibility
Rosenberg et al. (2022)	Comprehensive analysis of battery pack disassembly processes	(Different) Screws and adhesives are the main challenges for automated disassembly, manual disassembly is very time-consuming
Schäfer et al. (2020); Zhou et al. (2021)	Analysis of general battery pack recycling challenges	Safety challenges in the manual battery pack dismantling process, Irreversible joining technologies and materials
Wegener et al. (2014)	Disassembly concept for the Audi Q5 hybrid system	Time-consuming process
Wu et al. (2023)	General review about battery pack dismantling	A universal technology or disassembly method is not developed yet, Disassembly time and cost are a key challenges, Disassembly processes must be (fully) automated to be efficient
Xiao et al. (2023)	General overview about battery pack disassembly with focus on task management	Battery pack design variety is a challenge for automation, Currently mainly manual disassembly
Xu et al. (2022)	Assessment of automation potential for battery pack disassembly	Many different screws/adhesives
Zang and Wang (2022)	General overview about battery dismantling with focus on usage of robotics	Usage of robotics lowers costs and improves safety / efficiency, Challenges for automation due to large variety of designs, Poor accessibility of components requires many tools
Zhang et al. (2018)	Development of a generic tool and framework for disassembly	Dismantling is time-consuming because of the complexity of the battery pack in context of shape, size, and heterogeneity of the components used
2 different sources	Safety aspects in battery pack dismantling	The sources were not further investigated as they were not relevant for this paper.
4 different sources	Sustainability of battery pack dismantling operations	The sources were not further investigated as they were not relevant for this paper.
8 different sources	Hybrid battery pack dismantling concepts with human and machine or robot collaboration.	The sources were not further investigated as they were not relevant for this paper.

13 different sources	Re-X friendly design of battery packs	The sources were not further investigated as they were not relevant for this paper.
30 different sources	Digitalization in battery pack disassembly operations and the use of digital tools or concepts	The sources were not further investigated as they were not relevant for this paper.
21 different sources	Not relevant	The sources were not further investigated as they were not relevant for this paper.

Appendix B. Literature overview "Ablation"

Source(s) alphabetical	Technologies for electrode foil recycling	Technological advantages and enhancements	Technological challenges and critical factors
He et al. (2015)	Removal of active material through ultrasonic cleaning	Improved peel-off efficiency through ultrasonic pre-treatment	High effort to dismantle batteries manually down to electrode level
He et al. (2021)	Chemical removal of active materials, chemical dissolution of foil, Binder removal through heating, mechanical crushing, ultrasonic cleaning	Chemical removal: high yield, efficiency	Chemical removal: high cost, secondary pollution, long process-time
		Heating: efficiency	Heating: pollution through burning of organics, high energy consumption
		Mechanical crushing: efficiency, can be used as a pre stage for chemical treatments	Mechanical crushing: cross-contamination reduces efficiency of further hydrometallurgical processes
Liu et al. (2016)	Laser ablation	Only SEI was removed – not relevant for this paper	
Natarajan et al. (2022)	Overview with several technologies: Wet and dry grinding, Electrolysis, Cryogenic grinding, Dipolar aprotic solvent separation, Bio-derived solvent separation, Molten salt approach, Ultrasonic treatment, Thermal treatment, Acid or alkali separation, Mechanical grinding	Wet and dry grinding: High surface area and volume ratio	Wet and dry grinding: Binder cannot be separated, no detail for current collector separation from other components
		Electrolysis: Low solvent consumption, valuable secondary gas products	Electrolysis: High energy consumption
		Cryogenic grinding: High peel-off efficiency, no surface oxidation	Cryogenic grinding: Expensive liquid nitrogen, more economic
		Dipolar aprotic solvent separation: High separation efficiency	Dipolar aprotic solvent separation: High cost and toxic to environment, flammable
		Bio-derived solvent separation: High separation efficiency and waste utilization, on-toxic and biodegradable	Bio-derived solvent separation: Increases the complexity of the recycling process and cost
		Molten salt approach: Benign melt chemistry, high thermal and chemical stability, easy to regenerate	Molten salt approach: Salt residues are not easy to remove, design of operation cell is limited
		Ultrasonic treatment: Simple and reduces the separation time, reduces the usage of solvent, almost no emissions	Ultrasonic treatment: High power consumption, noise pollution, not easy to scale-up

		Thermal treatment: Operations are simple and convenient	Thermal treatment: High energy consumption and emission of toxic compounds
		Acid or alkali separation: Simple and convenient	Acid or alkali separation: Toxic and more wastewater generation
		Mechanical grinding: Easy operation	Mechanical grinding: Toxic gases emission, not possible to separate all components of spent LIBs
Ramoni et al. (2017)	Laser ablation	Only SEI was removed – not relevant for this paper	
6 different sources	Separation of current collector and active material through chemical processes	The sources were not further investigated as they were not relevant for this paper.	
89 different sources	Not relevant	The sources were not further investigated as they were not relevant for this paper.	

Appendix C. Process data for laser ablation of active material (LFP cathode foil)

TruPulse 5020 nano (Average Power: 200 W, spot diameter: 0,19mm)												
Nr.	Pulse Duration	Scan Speed	Hatch	Spot Size	Pulse Peak Power Density	Area Rate	Total foil area	Foil Weight before	Foil Weight After	Percentage Weight Difference	Process time	Comments
	[ns]	[m/s]	[mm]	[µm]	[MW/cm²]	[cm²/s]	[cm²]	[g]	[g]	[%]	[s]	
1	30	50	0,2	299	42,75	58,33	35	1,34	1,34	0,00	0,6	Active material not ablated (human visual inspection)
2	30	30	0,2	299	42,75	70,00	35	1,34	1,33	0,75	0,5	Active material not ablated (human visual inspection)
3	80	30	0,2	299	16,03	70,00	35	1,28	1,27	0,78	0,5	Active material not ablated (human visual inspection)
4	80	1	0,2	299	33,51	2,19	35	1,28	0,98	23,44	16	Active material not ablated (human visual inspection)
6	60	1	0,2	299	3,92	1,52	35	1,45	1,02	29,66	23	Active material not ablated (human visual inspection)
6	10	2,5	0,2	299	17,63							Active material not ablated (human visual inspection)
7	60	0,8	0,2	299	3,92	1,75	35	0,89	0,29	67,42	20	Active material ablated (human visual inspection)
7	10	1	0,2	299	28,22	1,75	35	0,89	0,3	66,29	20	Active material ablated (human visual inspection)
8	10	0,8	0,2	299	47,03	1,59	25	0,64	0,18	71,88	15,7	Active material ablated but aluminum foil was burnt (human visual inspection)
9	10	0,8	0,2	299	70,54	1,59	25	0,9	0,31	65,56	15,7	Active material ablated (human visual inspection)
10	170	5	0,2	299	15,77	1,67	35	0,89	0,22	75,28	21	Active material ablated but aluminum foil was burnt (human visual inspection)
10	120	10	0,2	299	5,88							
10	80	30	0,2	299	2,83							

Appendix D. Process data for laser ablation of active material (NMC cathode foil)

TruPulse 5020 nano (Average Power: 200 W, spot diameter: 0,19mm)												
Nr.	Pulse Duration	Scan Speed	Hatch	Spot Size	Pulse Peak Power Density	Area Rate	Total foil area	Foil Weight before	Foil Weight After	Percentage Weight Difference	Process time	Comments
	[ns]	[m/s]	[mm]	[µm]	[MW/cm²]	[cm²/s]	[cm²]	[g]	[g]	[%]	[s]	
1	10	1,5	0,2	299	58,78	2,98	58,50	1,82	0,76	58,24	19,6	Active material ablated (human visual inspection)
2	10	1,8	0,2	299	70,54	3,55		1,66	0,89	46,39	16,5	Active material ablated (human visual inspection)
3	10	1,5	0,2	299	70,54	2,97		2,16	0,59	72,69	19,7	Active material ablated but aluminum foil was burnt (human visual inspection)
4	10	1,8	0,2	299	58,78	3,55		1,49	0,9	39,60	16,5	Active material not ablated (human visual inspection)
5	170	5	0,2	299	7,68	0,90		1,74	0,38	78,16	65	Active material ablated but aluminum foil was burnt (human visual inspection)
5	120	10	0,2	299	5,88							
5	80	30	0,2	299	2,83							