CHALMERS
UNIVERSITY OF TECHNOLOGY

Development of an automated recycling process for car battery cathodes

Master's thesis in Production Engineering

YUCHEN WANG

DEPARTMENT OF INDUSTRIAL AND
MATERIALS SCIENSE

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2019
www.chalmers.se

DEPARTMENT OF INDUSTRIAL AND
MATERIALS SCIENSE
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden
www.chalmers.se

MASTER'S THESIS 2019

Development of an automated recycling process for car battery cathodes

YUCHEN WANG

CHALMERS
UNIVERSITY OF TECHNOLOGY

Department of Industrial and Materials Science
Chalmers University of Technology
Gothenburg, Sweden 2019

Development of an automated recycling process for car battery cathodes
YUCHEN WANG

Supervisor: Per Nyqvist, Industrial and Materials Science
Examiner: Björn Johansson, Industrial and Materials Science

Master's Thesis 2019
Department of Industrial and Material Science
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone +46 (0)31-772 1000

Gothenburg, Sweden 2019

Development of an automated recycling process for car battery cathodes
YUCHEN WANG
Department of Industrial and Materials Science
Chalmers University of Technology

Abstract

The electric vehicle becomes an alternative to fossil fuel-driven vehicles and its number has risen fast. However, the LIB's capacity is decreasing over time so that the battery recycling process has become a hot topic. Stena Metall Group initiated a project for developing a highly automated and efficient recycling process for recycling 18650 (cylindrical) batteries.

This thesis aimed to build an automated pre-treatment process for battery recycling and then evaluate the time consumption for the recycling line. The priority goal was to take out the cell from the battery housing and then separate anode/cathode foils. This work presented several theoretical proposals for each procedure and proposed a principal solution for the entire process which can be used on the production scale.

The pre-treatment was a mechanical process that had a limited effect on the recycling of lithium, cobalt and nickel, but it can further cooperate with the hydrometallurgical, bioleaching approaches and other chemical processes in order to recycle them. The proposed solution was according to the author’s experience and thinking during the entire project, but this solution was not verified or validated in practical.

In the end, this work also proposed several battery design suggestions for simplifying the recycling process.

Keywords: battery recycling process, 18650 battery, electric vehicle, production line

Acknowledgments

I would like to express my deep gratitude to my supervisor Per Nyqvist for patient guidance and idea inspiration, especially in the most crucial stages of this project.
I would like to thank Björn Hall and Sverker Skoglund for the supporting of experimental material and information sharing of lithium batteries.
I also would like to extend my thanks to Björn Johansson for providing feedback and motivating in the severe stages.
Finally, I wish to thank my parents and friends for their consideration and great support.

Yuchen Wang
Gothenburg, 2019

Table of Contents

List of acronyms

Acronym	**Unfolding**
LIB	Lithium-ion battery
PVDF	Polyvinylidene difluoride
HEV	Hybrid electric vehicle
PHEV	Plug-in hybrid electric vehicle
FCEV	Fuel cell electric vehicle
BEV	Battery electric vehicle
PRC	People's Republic of China
NMP	N-methyl-2-pyrrolidone
NMC	$LiNi_xMn_yCo_zO_2$
NCA	$LiNi_xCo_yAl_xO_2$
$LiPF_6$	Lithium Hexafluorophosphate
$/mt	US dollar price per metric ton
OEE	Overall Equipment Effectiveness

List of figures

List of tables

1 Introduction

1.1 Background

According to the influence of the greenhouse effect and the impact of climate change, the use of clean energy is replacing the fossil energy, especially in the automotive market. On one hand, the governments issued preferential policies and increased budgets on infrastructure to support the developing of clean energy vehicles. On the other hand, more and more people prefer to choose electric-drive and hydrogen-drive vehicles than traditional fossil vehicles.

Due to Tesla's successful marketing, lithium-ion battery vehicles have developed rapidly and have become the mainstream of clean energy vehicles. However, the lithium-ion battery's capacity is decreasing over time. Recycling of the batteries of electric vehicles has become a hot topic for recycling companies.

Battery recycling is considered an economically profitable project because essential metals such as cobalt and nickel are scarce and irreplaceable, and the price of these metals has increased year by year due to the increasing demand for lithium batteries. [1]

1.2 Stena Metall Group

Stena Metall Group initiated this project because they are interested in developing a highly automated and efficient process for recycling 18650 battery cells. Stena Metall Group is a leading recycling company. Operations include the production of aluminum from recycled material, the supply of steel products and components, financial operations and international trading in steel, and ferrous and non-ferrous metals and oil. Each year, Stena Metall Group recycles six million tons of waste. [2]

1.3 Aim

This work attempts to build an automated disassembly process for the 18650 battery. Compared to the flat battery cell, 18650 battery has a standard shape and size, which makes it easier to build a standard process for recycling. The priority goal is to take out the cell and then separate anode/cathode foils.

This work will mainly consist of:

- Development and presentation of one or more theoretical proposals for recycling the cobalt cathode from a standard cylindrical battery.
- Comparison of the existing disassembly processes and new proposals.
- Evaluation of the recycling process and give recommendations for implementation.
- Investigation and proposal for possible battery design changes in order to simplify the recycling process.

1.4 Limitations

This work aims to establish a disassembly process of a single battery cell, it will focus on proposing different ideas for each disassembly procedure. This disassembly process is only designed for the 18650 type battery. In the end, this work will suggest a principle solution, but it will not be implemented at testbed due to time constraints.

1.5 Research questions

This thesis work will try to answer the following four questions:

1. What are the physical and chemical properties of the batteries?
2. How are these properties used to support recycling?
3. According to current recycling research, which parts of the disassembly processes are challenging to be automated?
4. How long does it take to complete the entire recycling process?
5. What kind of design can simplify the battery recycling process?

2 Background information

This chapter aims to deliver a precise and profound background of the lithium-ion battery (LIB) and the current market of its recycling. This information provides an understanding of the current recycling procedures. Moreover, the analysis and statistics of the current recycling procedures can help to find a suggestion of an automated process.

The research study is ongoing throughout the thesis work. Information comes from databases: Scopus, Google Scholar, and Chalmers Library.

The literature survey covers cylindrical battery properties, the statistics of the electric vehicle markets and the existing disassembly methods. Through this survey, the author has narrowed down on the potential automated processes and further focus this research on robotics and safety issues.

2.1 18650-battery

A cylindrical battery with 18mm diameter and 65mm in length is called 18650 battery. The last number 0 means the battery is cylindrical. In the electric vehicle market, the major customers of this battery are Tesla Motors, for example, the Tesla Model S is powered by 7104 pieces of 18650 battery. The battery system is composed of 16 battery packs connected in series, and each battery pack includes 444 pieces of 18650 battery. However other companies choose the flat battery instead. The flat battery design has no standardization of the shape yet, but its flexibility can meet custom requirements of the companies.

The 18650-battery is composed of two thin electrode foils. The anode foil is a piece of metallic copper, and the cathode is aluminum. Both metal foils are bonded by the active material of the li-ion battery, thus containing lithium and cobalt as a fine powder aggregated with a polymeric binder (PVDF) and rolled up in cylindrical shape [3].

The 18650 battery can be produced in high-volume batch because it has a standard size and shape. A winding machine creates an automated way to produce battery cells. Furthermore, the cylindrical shape has a better heat release consistency compared to the flat battery.

2.2 Lithium-ion battery

A LIB consists of an anode, a cathode, ion-conducting electrolyte and two pieces of separators. The separator is a porous membrane used for isolating the two electrodes from each other. Different electrode materials determine different battery power density. The following explanation shows the material composition of the NMC ($LiNi_xMn_yCo_zO_2$) as well as the reaction.

Anode: Graphite and amorphous carbon compounds are attached on the anode collector – the copper foil, which are used to embed lithium.

Cathode: The aluminum collector carries the mixed oxides of cobalt, nickel, and manganese.

Reaction: Figure 1 shows the general reaction of the lithium-ion battery. When the battery is discharging, the lithium-ions migrate from the anode through the electrolyte and then separator to the cathode. At the same time, the electrons as electricity carriers migrate from the anode via an external electrical connection (cable) to the cathode. This process is reversed during charging [4]. In the NMC battery case, M in compounds $LiMO_2$ and $Li_{(1-x)}MO_2$ represents the metals Mn, Co, and Ni [5].

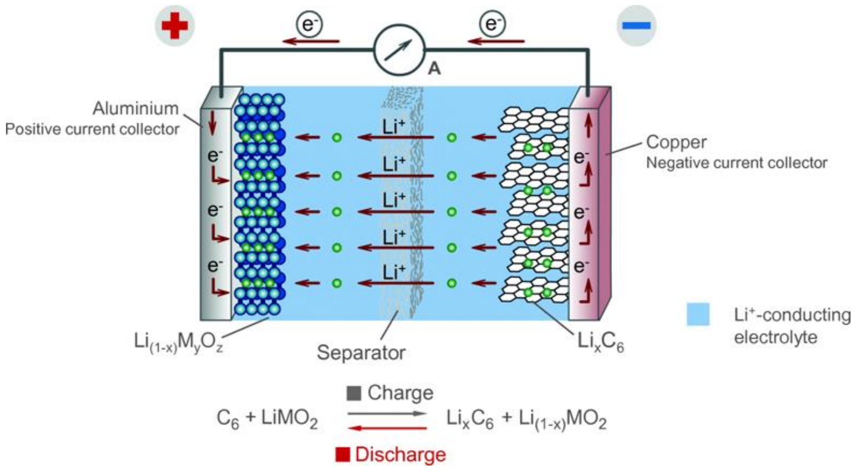


Figure 1 Discharging reaction of LIBs [4]

The NCA ($LiNi_xCo_yAl_xO_2$) battery has a similar reaction as the one explained above, but the cathode electrode materials are composed of cobalt, nickel, and aluminum, not NMC.

2.2.1 Materials for battery components

Component	Materials [1][6]	Length [7]
Cathode	Lithium compound (e.g. $LiCoC_2$, $LiFePO_4$, $LiMn_2O_4$, $LiNi_xCo_yAl_xO_2$) on aluminum foil	52.0 cm
Anode	Graphite or carbon composite on copper foil	53.7 cm
Separator	Polymers (polyethylene, polypropylene)	/
Electrolyte	Mixtures of propylene carbonate, ethylene carbonate, dimethyl sulfoxide, dimethyl carbonate or diethyl carbonate with lithium salts such as $LiPF_6$, $LiBF_4$, $LiCF_3SO_3$, $Li\ (SO_2CF_3)_2$	/
Binder	Polyvinylidene difluoride (PVDF)	/
Electric lead	Copper or aluminum	/
Housing	Galvanized steel, aluminum	/

Table 1 Materials for Battery Components

Table 1 describes the included components in LIBs. When using the material's price to evaluate the battery, the cathode materials occupy almost half of the total price (Figure 2 describes the cost distributions of a LIB). In the xEV industry, the cathode materials compose of ternary layered oxides. The most successful doping ternary layered oxides are NMC ($LiNi_xMn_yCo_zO_2$) and NCA ($LiNi_xCo_yAl_xO_2$). Cobalt and nickel are widely used in cathode materials and are irreplaceable [8]. Cobalt controls the rate of charging and discharging and its high proportion decreases the charging/discharging time leading to longer battery life. Nickel is related to electrochemical capacity, its high proportion increases the battery capacity [9]. Nearly half of the cost of the battery is owing to the cathode material used such as cobalt (48,680 US$/mt (US dollar per metric ton), 99.8% purity) and nickel (10,124 US$/mt, 99.8% purity). Simultaneously, it makes the battery recycling economically profitable. It is worth mentioning that the price of anode foil - copper, also has a high price: 5624 US$/mt (class A, LME, average prices from September 2016–August 2017) [1].

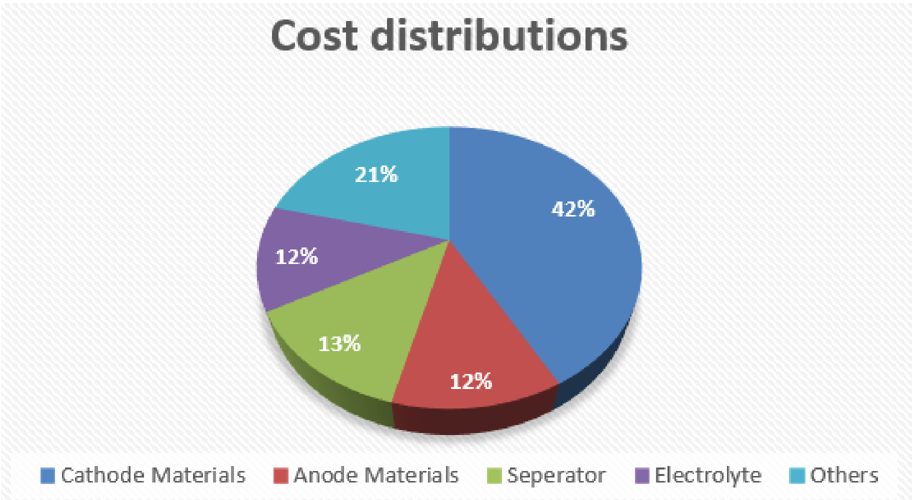


Figure 2 Cost distributions of LIB [8]

2.2.2 The binder: PVDF

PVDF is a perfect binder in LIBs owing to its non-flammable and non-dripping nature. It displays excellent properties within the criteria of chemical resistivity, mechanical strength, processability and favorable piezoelectric and pyroelectric properties. As a binder, it fulfills its functional duties such as to bond cathode/anode material with the metal foil. It's a semi-crystalline, high purity thermoplastic fluoropolymer which is self-extinguishing with a melting point of 178 °C. PVDF is inert to a broader range of chemicals, although it dissolves in organic solvents such as esters and amines as reported [10].

The best way to decompose PVDF is to use NMP (N-Methyl-2-pyrrolidone). NMP is an excellent solvent for PVDF (solubility around 200 g/kg of solvent), this property can be used for separating electrode materials from metal foil. The recovery of both copper and aluminum in their metallic form can be done by filtrating them out from the NMP solution. Both metals are reusable after adequate cleaning. Simultaneously, NMP is also possible to reuse for many cycles because of the high solubility for PVDF. [7]

The process to separate PVDF from metal foil has been highlighted, briefly the separation can be done in the following two ways. Either, Ultrasonic Washing of metal foils immerses NMP solution for 20 min at 40 Hz & 100 W [11] or simple metal foil immersion in NMP at 100℃ for 1 hour [7].

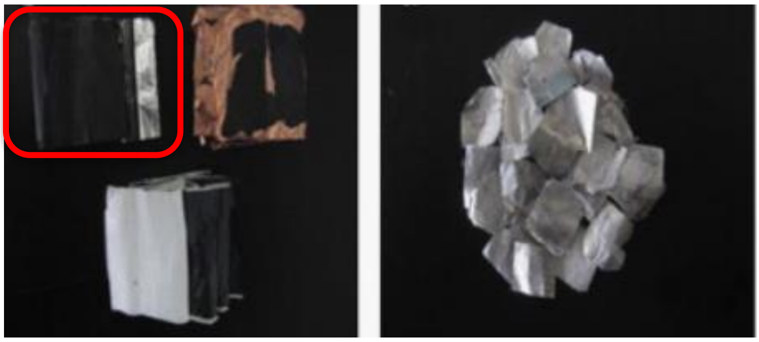


Figure 3 Cathode foils after immersion in NMP [11]

2.3 LIBs market

According to the record and the future forecast of the current LIBs market, the demand is expected to triple in 2025 (210GWh) compared to 2016 (78GWh). EVs are the most substantial proportion which occupied half of the total demand. [8] [12]

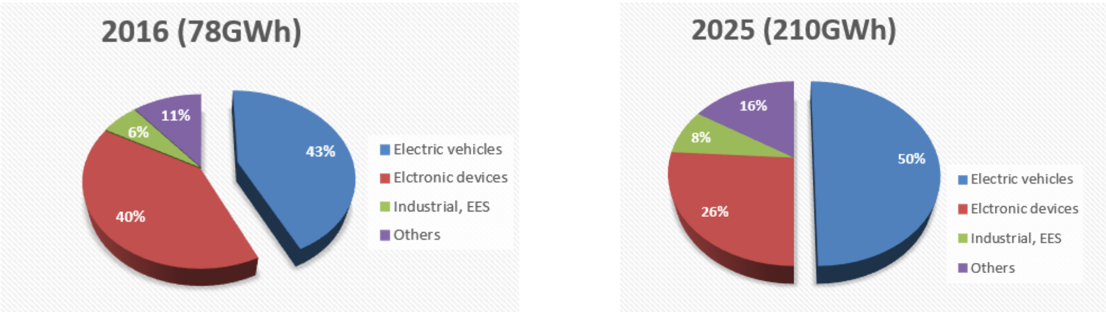


Figure 4 The global demands and main applications of LIBs in 2016 and 2025 [12]

2.3.1 xEV market

All vehicles which are powered by LIBs can be summarized as xEVs. This includes Hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV), fuel cell electric vehicles (FCEV), and battery electric vehicles (BEV). [1].

Figure 5 shows the annual sales of BEV and PHEV in EU, USA, and China (PRC) market from 2010 to 2019. The lifecycle of electrical buses and cars is around 12 to 15 years, respectively, the number is assumed by combustion engines' lifecycle since there is no data for xEVs' yet. Figure 6 describes the estimated return flows of battery wastes from 2012 to 2025 by number (a) and weight (b). [1]

Climate change urges not only the growth of xEVs' market but also a rapid consumption of constituent materials for LIB production. To stabilize rare metal prices and handle spent batteries in a proper way, the need for an effective recycling process is of high demand.

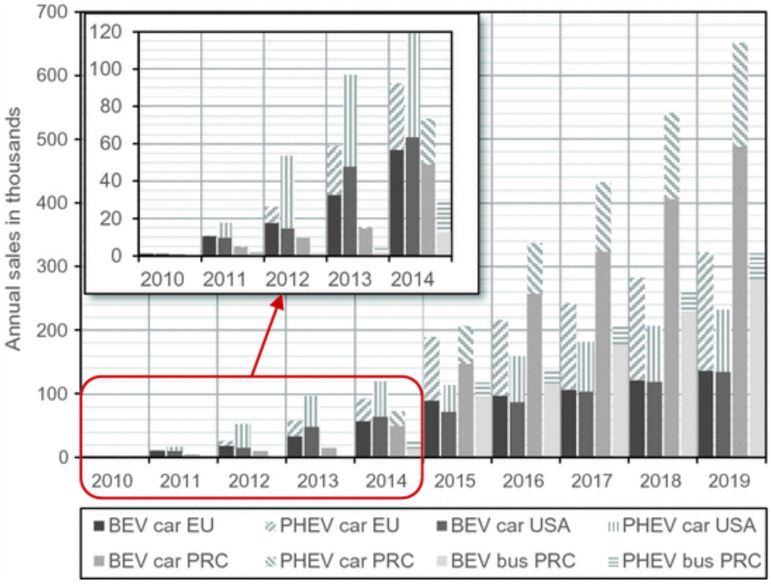


Figure 5 Annual sales of BEV and PHEV in US, EU and PRC from 2010 to 2019. [1]

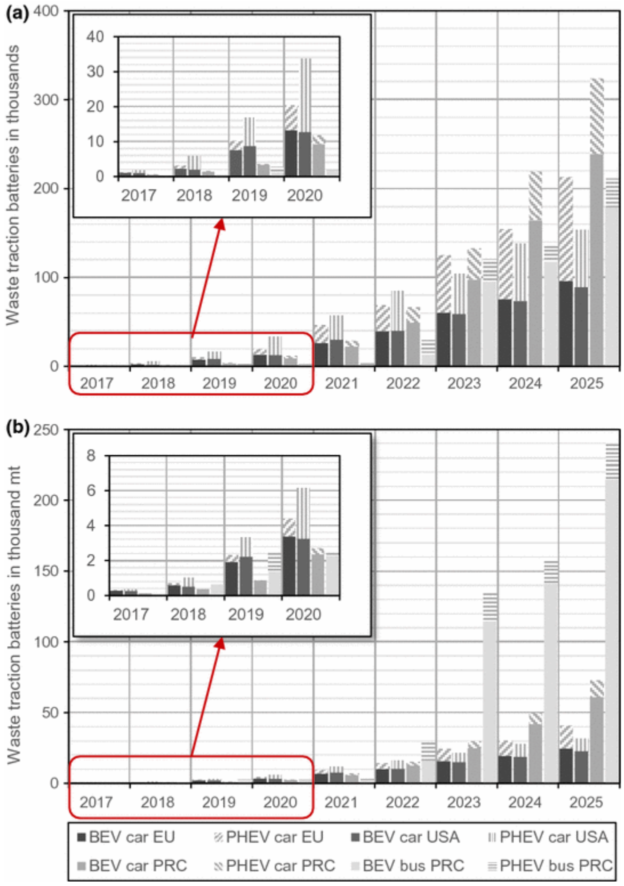


Figure 6 Annual battery wastes from 2012 to 2025: a) The waste traction batteries by number; b) Waste traction batteries by weight. [1]

2.3.2 Tesla in the European market

Table 2 shows the number of sold Tesla cars across European countries from 2013 to 2018. It is worth noting that Tesla is a major buyer of 18650 batteries from suppliers.

Country	***2013***	***2014***	***2015***	***2016***	***2017***	***2018***
Norway	1983	4040	4039	3481	8460	8614
Netherlands	1195	1469	1891	2149	3317	8604
Germany	204	814	1582	1908	3332	1905
Switzerland	213	496	1556	1701	2024	1452
France	37	328	708	945	1368	1252
Sweden	5	265	996	1160	1283	1228
Belgium	148	521	820	859	1151	878
Austria	50	136	492	717	900	473
Italy	8	52	134	241	482	464
Spain	1	15	10	57	388	326
Finland	2	94	146	121	248	172
Ireland	N/A	N/A	N/A	N/A	49	120
Denmark	112	460	2736	176	98	96
Luxembourg	N/A	N/A	N/A	N/A	155	86
Czech Republic	N/A	N/A	N/A	N/A	80	85
Slovenia	3	n/a	8	11	11	11

Table 2 Sold Tesla cars in partial European countries [13]

According to Table 2, there are around 1200 Tesla cars sold to Sweden every year since 2015. The estimated lifecycle of electric cars is around 15 years, this implies that by 2033, the country will have around 1200 Tesla cars that reach the end of their life. Therefore, recycling would be a major factor in developing a more sustainable and circular economy around the car.

2.4 Current disassembly methods

According to the survey of current disassembly methods, pyrometallurgical and hydrometallurgical processes are the two major methods for cathode material recycling [14]. Other than these, bioleaching is another emerging recycling method but it is not mature enough for batch-level production. Table 3 shows partial research of the recycling methods:

Process	Reagent	Recycle result	Reference
Hydrometallurgical	Acid leaching tests with H_2SO_4	Al: 55 wt.%, Co: 80 wt.%, Li: 95 wt.%	[15]
Hydrometallurgical	Acid leaching with H_2SO_4 and H_2O_2	Al: 85 wt.%, Co: 37 wt.%, Li: 55 wt.% Cu: 1 wt.%	[3]
Hydrometallurgical	Acid leaching with HNO_3 and H_2O_2	Co: 99 wt.%, Li: 95 wt.%	[16]
Hydrometallurgical	Acid leaching with HCl	Co: 99.5 wt.%, Li: 99.9 wt.%, Ni: 99.8 wt.%, Mn: 99.8 wt.%	[17]
Hydrometallurgical	Leaching with $C_4H_5O_6$ and H_2O_2	Co: 93 wt.%, Li: 94 wt.%	[18]
Hydrometallurgical	Leaching with organic ascorbic acid	Co: 94.8 wt.%, Li: 98.5 wt.%	[11]
Pyrometallurgical	Fusion with $KHSO_4$	Co: >99 wt%, Li: 50 wt%, Mn: >99 wt%	[19]
Bioleaching	Sulfur-oxidizing iron-oxidizing bacteria	Co: >90 wt.%, Li: 80 wt.%	[20]
Bioleaching	Acidithiobacillus ferrooxidans	Co: 65 wt.%, Li: 10 wt.%	[21]

Table 3 Existing recycling methods

All three methods above are focused on the recycling of cathode electrode materials. Compared to the pyrometallurgical method, the other two methods require a pre-treatment process to separate the cathode/anode foil.

2.4.1 **Pyrometallurgical recycling**

Pyrometallurgy is a method that removes the organic binder by incineration, simultaneously, the metallic compounds are subjected to a redox reaction to recover low-boiling metals and compounds in their condensed form. The metal in the slag is recovered by sieving, pyrolysis, magnetic separation and chemical methods. The pyrometallurgical method is an advanced method for large-scale recycling, but the drawback is that it generates polluting gases during the process. This method requires high-quality and complex equipment in order to satisfy the temperature and purification conditions.

2.4.2 Hydrometallurgical recycling

Hydrometallurgy is a method that is selectively dissolving the cathode electrode material and separating the valuable metal elements by chemical reagents. Compared to the pyrometallurgical method, hydrometallurgy has a low requirement of equipment which makes it cheaper. According to the survey, hydrometallurgy is a mature method for small and medium-batch recycling production.

2.4.3 Bioleaching recycling

Bioleaching is a method that utilizes the metabolic processes of bacteria to achieve selective leaching of cobalt and lithium. However, this method has not reached the maturity to be applicable in large scale industries because even though the bacteria are reusable, their cultivation requires harsh conditions and the leaching efficiency is low.

2.4.4 Summary

On the laboratory scale, most of the research is focused on hydrometallurgical and bioleaching methods because they do not depend on complicated and expensive equipment. Instead, it needs a pre-treatment process to separate the anode/cathode foil first. The pre-treatment process includes: cutting the battery housing, taking out and unfolding the cell, separating anode and cathode foils, cut these foils into small pieces. Then the treated foils continue with hydrometallurgical or bioleaching methods to separate different materials. According to the current survey (Table 3), the pre-treatment process is performed manually.

Pyrometallurgy is a more suitable method for the production plant scale. High-standard equipment brings efficiency and large-batch capability. The procedure of the pyrometallurgical method includes thermal treatment, high-speed shredding, and calcination. A spent LIB needs to go through thermal treatment (150 °C muffle furnace for 1 h), high-speed shredder, vibration screening (to separate electrode materials and the cathode/anode foils), burn off carbon and binder (700–900 °C for 1 h), grind and dry (ball mill to ground electrode materials and then dry it in 60 °C in an oven for 48 h) [21]. Afterwards, the material powder is further sent for separation via several chemical processes.

According to the above information, the battery recycling process is composed of a mechanical process (to separate cathode materials and others) and a chemical process (to extract valuable materials). Compared to the pyrometallurgical method which needs to execute the incineration procedure, hydrometallurgical and bioleaching methods can save more material. Therefore, this thesis work attempts to improve and optimize the pre-treatment process by automation. Since the chemical processes adopted for the extraction of valuable materials is advanced enough for practical applications, it is not covered in this work.

2.5 Hazards during disassembly

According to the survey, the potential hazards during battery recycling can be divided into three aspects: electrical hazards, fire/explosion hazards and chemical hazards. Here, hazards that may happen during the disassembly process are discussed briefly.

2.5.1 Electrical hazards

It is very dangerous to disassemble a charged battery. The battery can emit direct current that results in electric shock leading to muscular paralysis and blood electrolysis [22]. Using conducting cutters to open the battery housing may lead to short circuit.
In order to avoid electrical hazards, it is necessary to discharge batteries before the recycling process. Furthermore, the operator needs to use protective gloves and glasses to reduce the possibility of electric shock.

2.5.2 Fire/Explosion hazards

The electrolyte solvent in the LIB cell is a mixture of linear carbonates which is flammable and easily reacts with aerial oxygen, such a chemical reaction leads to fire and explosion hazards [22]. On the production scale, the recycling process should be performed in a pure inert gas environment to avoid solvent's reaction with aerial oxygen, for example, perform in argon gas. In addition, a flame retardant for example HFC-227ea should be prepared in advance. The purpose of the flame retardant is to rapidly drop temperature and decrease oxygen concentration to stop chemical reactions [23]. On the laboratory scale, to use sand as the flame retardant and execute the discharge process is a much cheaper and easier option to avoid fire and explosion hazards.

2.5.3 Chemical hazards

One of the carbonates in the electrolyte is $LiPF_6$ (lithium hexafluorophosphate) [6].
The $LiPF_6$ can dissociate to LiF (lithium fluoride) and PF_5 (phosphorus pentafluoride) in non-aqueous solvents:

$$LiPF_6(sol) \rightleftharpoons LiF(s) + PF_5(sol)$$

Moreover, it can react with water to generate LiF, HF (hydrofluoric acid) and POF_3 (phosphoryl fluoride):

$$LiPF_6(sol) + H_2O \rightleftharpoons LiF(s) + 2HF(sol) + 2POF_3(sol)$$

The generated products from these two reactions are toxic and acidic [24]. Therefore on the plant scale, the production line should have a gas purifier and each equipment should be monitored in real-time to avoid acid corrosion damages. The toxic and acid emissions against environment safety can be ignored for the lab scale, however, the operator should put on protective gloves and glasses as there are still human safety risks.

3 Experiments

To design an automated recycling process, the author performed several manual disassembly experiments in the laboratory. All appropriate safety measures during the experiments were taken, however, the operator took off the gloves to provide clear and insightful images as shown below once the sample was safe to touch.
Figure 7 shows a typical LIB construction:

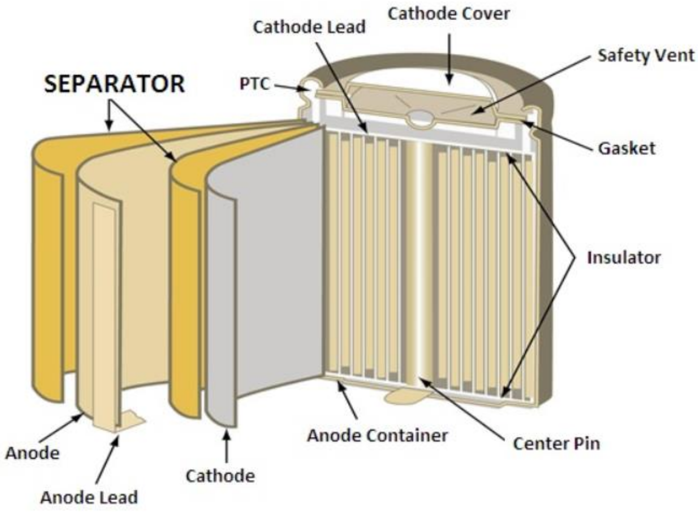


Figure 7 Typical lithium-ion battery construction [25]

3.1 LIB construction

Figure 8 shows an example of the 18650 battery. This type of battery consists of two parts, a cylinder housing and an internal cell (Figure 9).

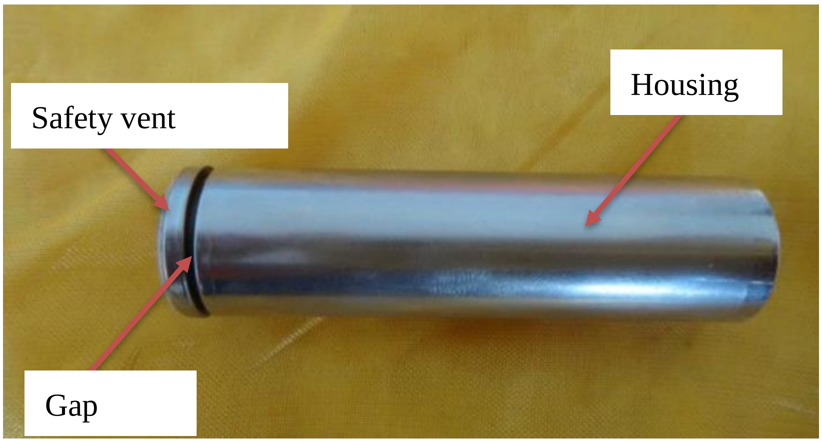


Figure 8 A 18650 battery

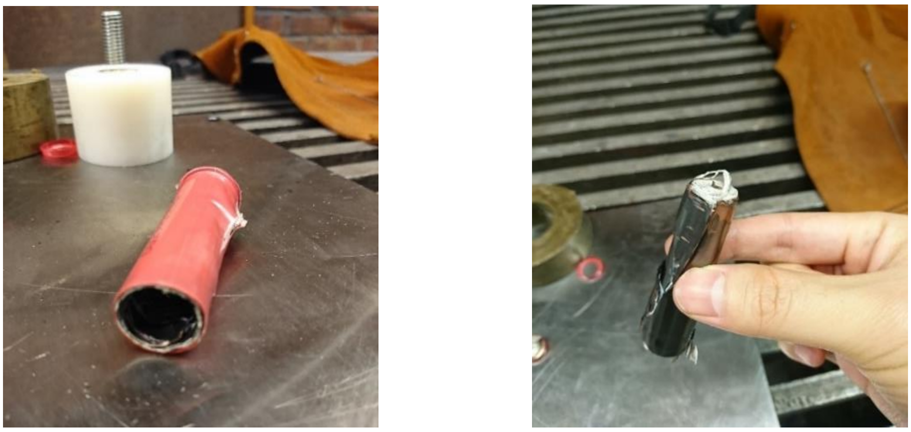


Figure 9 a) The housing with plastic shell (left), b) The cell (right)

The housing is covered by a plastic shell. Upon removing the plastic shell, the safety vent is located on one side of the housing. The vent is used to release the internal air pressure to prevent short circuits and explosions. Practically if the internal pressure is too high, gases will raise the vent up to cut off the electric lead thereby avoiding further reaction. There is a small gap connecting the safety vent and the housing.
According to the different lengths of the safety vent, two different battery designs were found in the experiments as shown in Figure 10. Here, one has a wider gap between the safety vent and the battery as can be seen. Figure 11 shows that the lengths of the safety vent between the two batteries are variable (4.5 mm and 5.5 mm in this case).

Figure 10 Different safety vent designs

Figure 11 Different lengths of safety vents

Figure 12 shows the diameter and length of the internal cell are 16mm and 60mm, respectively. According to disassembly experiments, some batteries had a center pin (a hollow metal stick which is shown in Figure 13), others kept the center pin position as hollow. The pin/hole’s diameter is around 3mm.

Figure 12 Diameter of the cell (left), length of the cell (right)

Figure 13 A center pin

Figure 14 shows an example of the battery cell. It is a cylindrical roll that is wound by four films. These films run along the length of the cell and are made up of copper foil (anode electrode), plastic film (separator), aluminum foil (cathode electrode) and another plastic film (another separator). The anode material used in Tesla batteries is graphite bonded on the copper foil, and the cathode material is NCA bonded on the aluminum foil. The binder PVDF uniformly bonds graphite/NCA on the metal foils.
The cell winds in counter-clockwise direction if seen from the top view. It should be noted that the safety vent is considered as the top side and the other side is considered as the bottom. The unwinding procedure needs to set a clockwise direction as the rotation direction to unwind a cell.

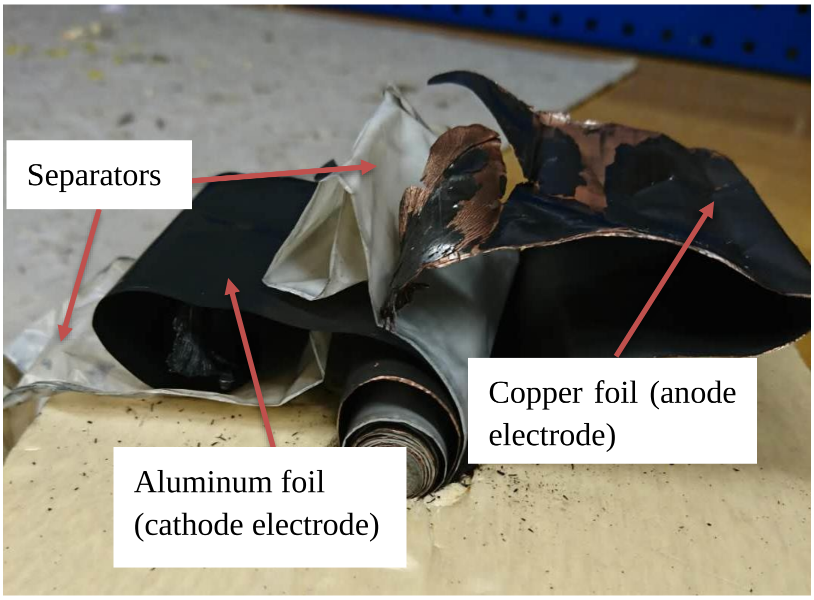


Figure 14 The cell

Batteries with the condition that NCA/graphite falls off from the cathode/anode foils and gathers around the separators are said to be undergoing battery aging. The cause of this situation is the loss in the activity of the binder resulting in materials slip from the metal foils. Figure 15 shows the difference between ordinary batteries and aging batteries.

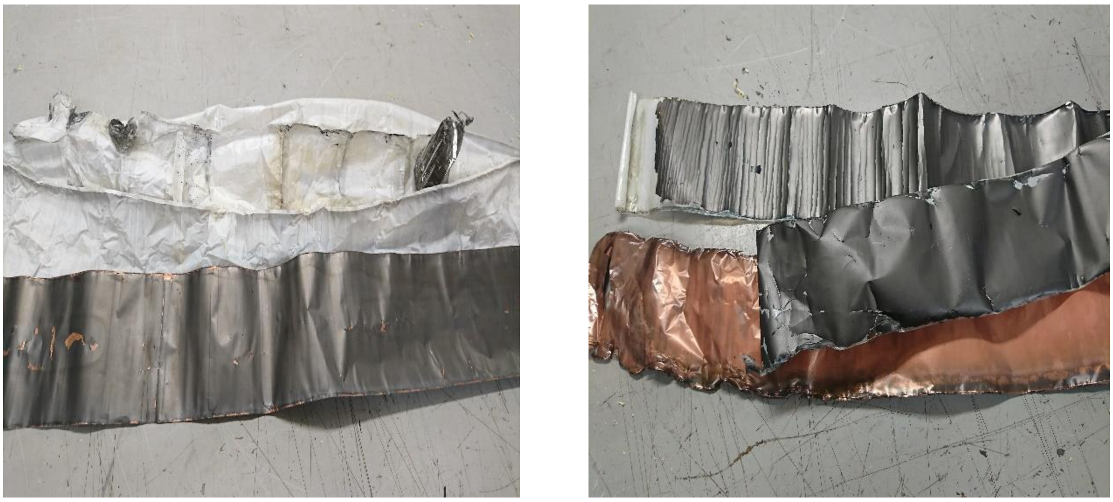


Figure 15 a) An ordinary cell, b) An aging cell

3.2 Battery disassembly process

Figure 16 shows the battery recycling process:

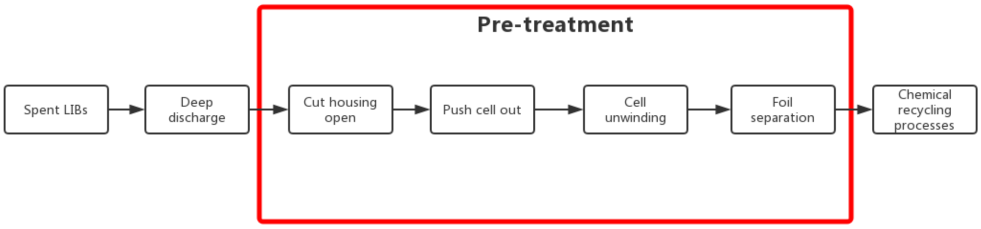


Figure 16 Recycling process flow

The priority of this thesis is to recycle materials from the cathode electrode and also to save as much material as possible. Only discharged batteries can be put in the disassembly line.

In order to find out the requirements for an automated process, laboratory experiments were carried out. The pre-treatment includes four procedures which are shown in the red box in Figure 16: 1) Cut housing open, 2) Push cell out, 3) Cell unwinding and 4) foil separation. Each procedure includes several steps.

3.3 Procedure one: cut housing open

3.3.1 **Manual procedure**

Figure 17 shows an example of a cylinder cutter tool. It is used to hold and cut batteries in the manual procedure.

Figure 17 The cylinder cutter tool

The plastic shell covering the housing was a problem in the manual procedure because it was moveable and obstructed the cutter to work on the housing directly. Therefore the first step was to take off the plastic shell.

In order to push the cell out, both edges of the housing should be cut open. On the top side, the cutter can locate the gap (4.5mm to 5.5mm below the top edge) to avoid damaging the cell. On the bottom side, there was a mark at 4mm above the bottom edge which can be used to locate the cutter (Figure 18). It should be noted that the cell and the housing are tightly fitted (Figure 19), it was difficult to remove the cut shell if the cutting position was far from the edge.

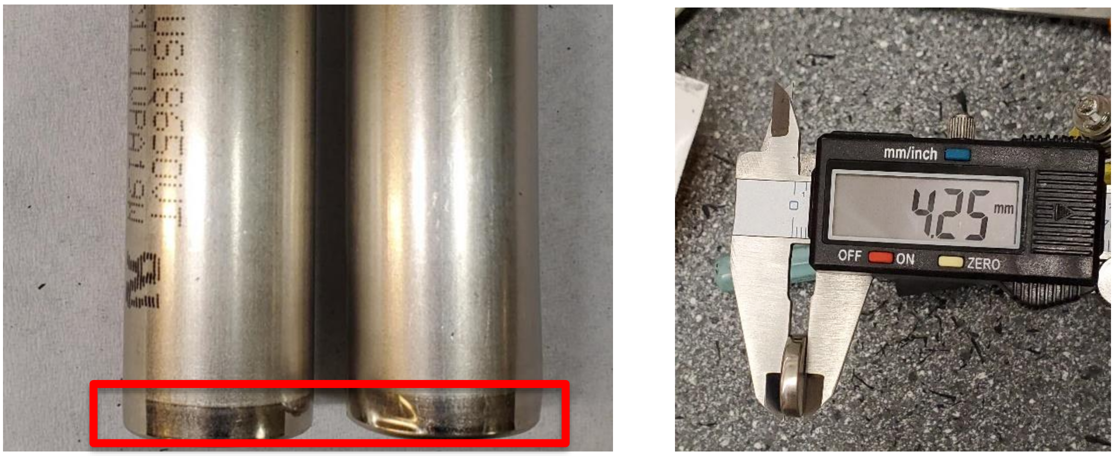


Figure 18 A mark at 4 mm above the bottom edge

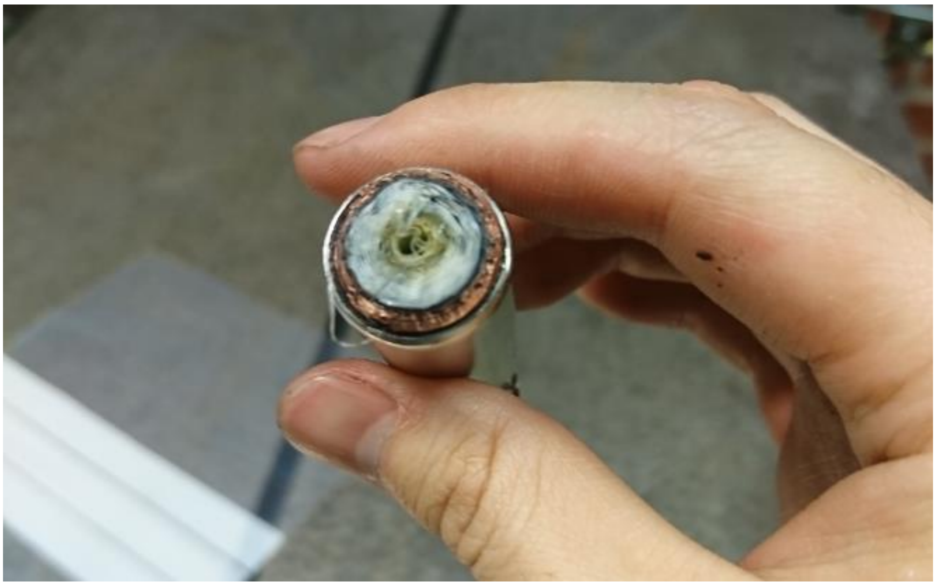


Figure 19 Cell and housing are tightly fitted

The cutter tool made a circular cut which kept the cells intact and made the cells longer than the housing. However, its disadvantage was that the circular cut cannot cut off the connection between electric leads and the housing (Figure 20), additional cutting step was required afterwards.

Figure 20 After circular cut

Thinking after experiments

Cut the safety vent edge first. The inner gases generated during charging and discharging step, gather around the safety vent. According to experiments, a loud burst only happens if the bottom edge opens before the top edge. Therefore, starting from the top seems a safer option.

The vent positions. Different battery brands have different designs of the safety vent which results in different lengths, but batteries in the same pack should be the same design. Therefore, on the production scale, the vent length should be measured before the recycling of each pack. Since the length of the safety vent is close to 4mm which is the color difference from the bottom edge, the vent length can be used as a standard to cut both edges.

According to the manual experiment, two problems hindered the automated process: 1) the cutting procedure needed two hands to assist and 2) the cutter tool needed multiple adjustment. Therefore, an automated procedure requires some tools and fixtures to 1) hold the battery in place, 2) locate the cutting position 3) and then cut it.

In details, the fixture used to hold the battery should be stable and sturdy, it should ensure that the battery cannot move during the cutting.

The circular cut used in the manual procedure should be replaced by a vertical cut. The change will lose some materials under the bottom edge cutting, but it avoids the additional step for cutting the electric leads. Since the priority goal is to build an automated recycling line, the material loss is acceptable.

The plastic shell obstructed the cutting step in the manual procedure, but it does not hold significance when the cutter is performed in an automated line. On the production scale, the plastic shell can be kept.

Based on the above information, two proposals were made for this procedure.

3.3.2 **Proposal 1: bench pit and press plate**

The battery can be secured using a bench pit and a press plate. The bench pit is an area on the workbench that can fit a lay-flat battery, the battery gets stuck in it to prevent translation. Next, the press plate presses on the battery to prevent rotation. Then, two cutters move down and cut both edges off, the vertical cut also cut off the electric leads during this step. The example model can be found in Appendix A a).

3.3.3 Proposal 2: battery holder

The battery can be secured using a cylindrical battery holder, it holds the battery upright and prevents translation and rotation. In addition, this proposal also requires a clamper-cutter tool that is used to pick up the battery and cut battery edges.

At the beginning, the clamper takes one battery to the holder. When the battery is fixed, the cutter goes down to the gap and cuts the top edge off. Next, the clamper picks up the battery and flips it, so that the bottom edge is on the top. Afterwards, the holder fixes the battery again and the cutter cuts the bottom edge off. The cutter performs a vertical cutting to avoid an extra step of cutting off electric leads. The example model can be found in Appendix A b).

Unwinding direction. It should be noted that the battery is flipped once in this proposal, which means the cell needs to be rotated in a counter-clockwise direction for unwinding.

Improvement of the battery holder. The battery holder can be used to fix the battery in the pushing procedure if the holder base has a 16mm hole as Figure 21 shows. The cell can be released through the hole while the housing is still blocked by the holder.

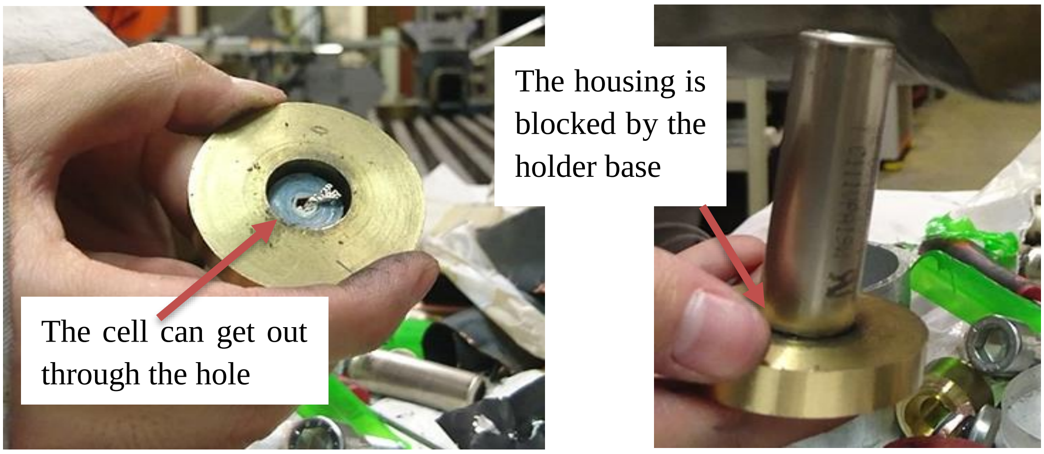


Figure 21 A hole on the holder base

3.4 Procedure two: push cell out

The next process is to push the cell out of the battery housing. Since the housing and the cell fit tightly, gravity is not enough to release the cell. This procedure requires a cylindrical pusher to push out the cell. A vice and a hydraulic press were used to provide the required force in this procedure. Most experiments were tested on the hydraulic press because it had a force gauge. Figure 22 shows examples of a hydraulic press and a vice.

Figure 22 a) Example of a hydraulic press [26]and b) A vice [27]

In this procedure, pushing results were checked in accordance with different diameters of the pushers. The pushing procedure was verified in both vertical (Figure 32 a)) and horizontal direction (Figure 23 b)).

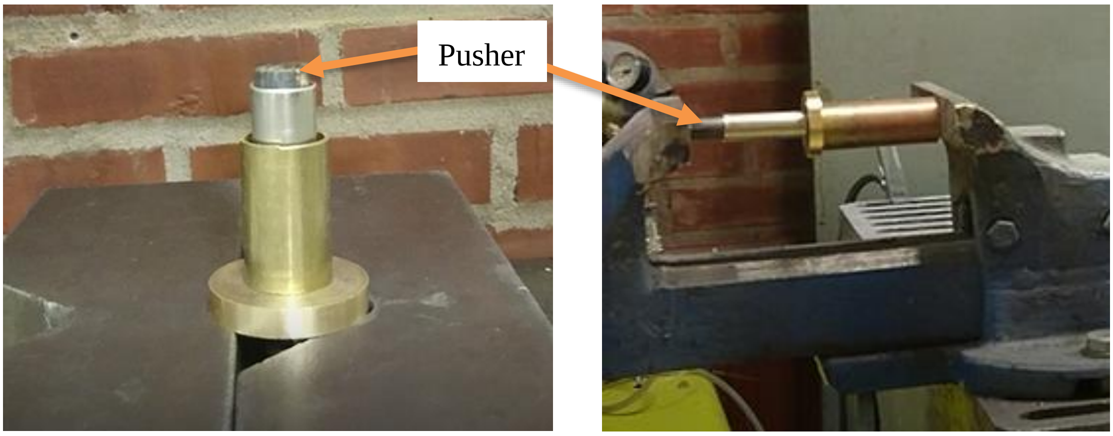


Figure 23 a) Vertical push, b) Horizontal push

As Figure 24 shows, the double-headed press - HIAB hydraulic press H100 was used in experiments. Here only “dornpress” with a weight range from 0 to 5 ton was used.

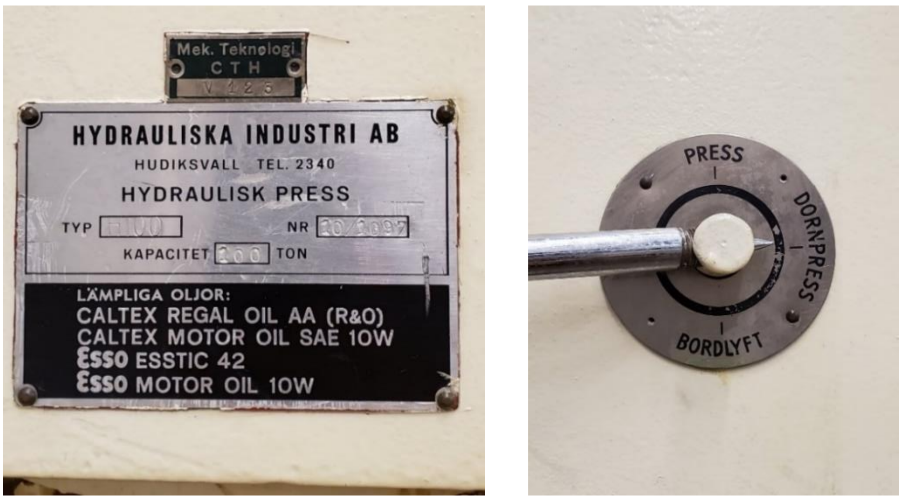


Figure 24 HIAB hydraulic press H100

3.4.1 Trial 1: 16 mm pusher

The first trial was to push the 16mm cell by a 16mm pusher as shown in Figure 25 a). The trial results showed that this procedure could successfully separate the housing and the cell. However during the pushing step, the pusher rubbed against the housing wall and caused deformation of the housing, so that the cell was torn during the pushing and resulted in an uneven edge as shown in Figure 25 b).
It requires around 5000N force to push a 16 mm pusher in the housing, Figure 26 a) shows the value from the force gauge.

Figure 25 a) 16mm pusher, b) The uneven edge is marked in red

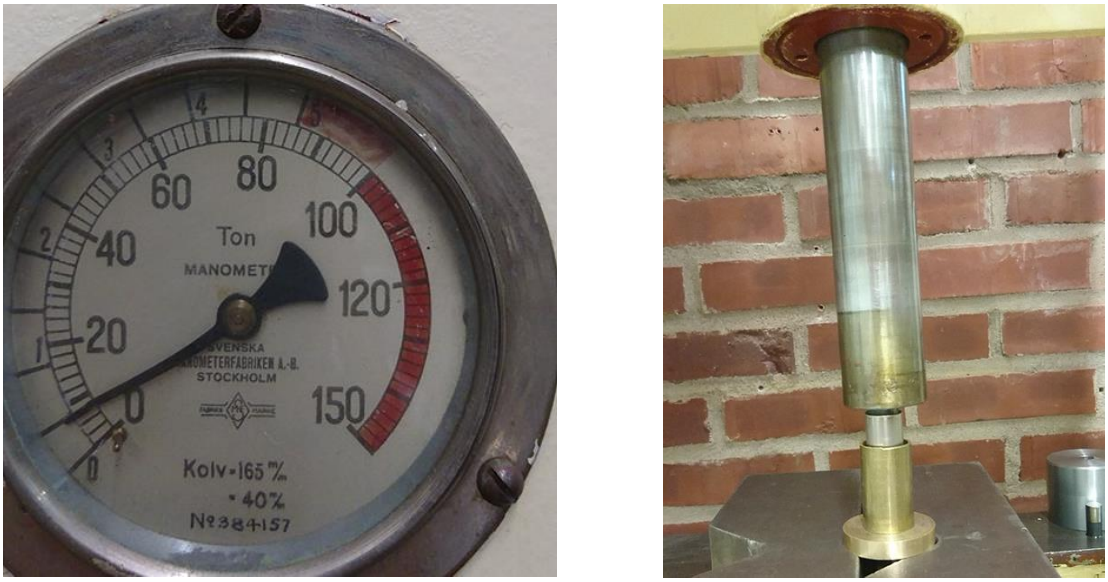


Figure 26 a) 500kg for pushing the 16mm pusher, b) The front view of the hydraulic press in the push step

3.4.2 Trial 2: 13 mm pusher

Considering the uneven edge problem could obstruct the unwinding procedure, the other proposal was implemented. As Figure 27 a) shows, a 13mm pusher can avoid the pusher rubbing against the housing wall and further avoid generating an uneven edge. After pushing, the cell was still intact but the partial cell remained in the housing. The pushing force decreased to around 1000N (Figure 28). Two options for the next step, 1) Actively cut off, 2) push the entire cell out.

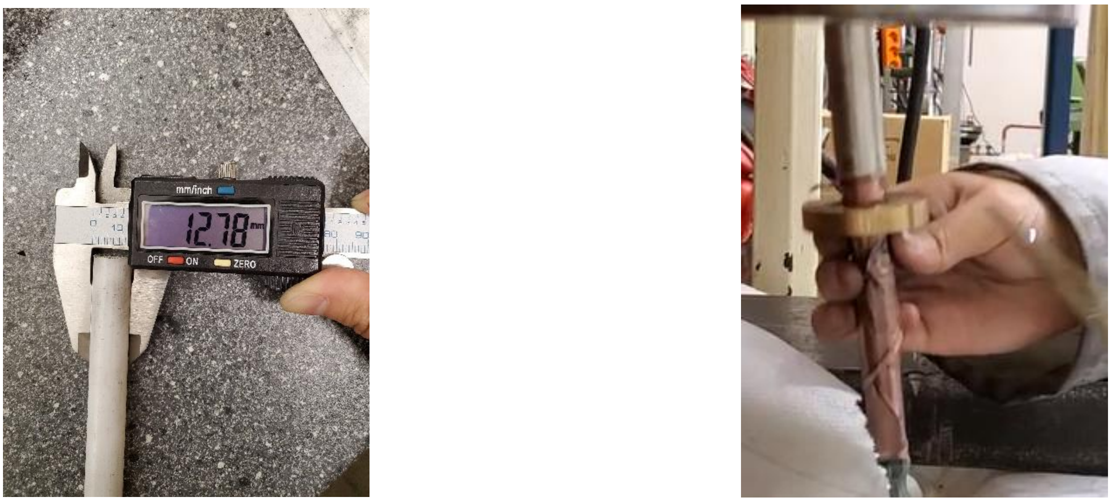


Figure 27 a) 13mm pusher, b) The result of pushing

Figure 28 The press provides 100kg to push 13mm pusher

3.4.2.1 Actively cut off

After pushing, the pushed-out battery was solid but the part still connected to the housing was hollow. In order to continue the process, the hollow films should be cut off to create an even edge.

3.4.2.2 Push the entire cell out

The second option was to push the entire cell out. The remaining battery was gradually pushed out by winding on the pusher (Figure 29, a)). Based on the trials, this option required a 230mm length pusher (Figure 29, b)).

This approach was inconsistent in experiments and led to unfavorable tore cells during pushing. According to the author's analysis, the reasons could be 1) the hydraulic press head needed to press on the pusher and then provided force to push the cell, mismatched joint led to the push not perpendicular to the workbench 2) the battery was constantly stretched during pushing eventually caused it to break.

*Figure 29 a) An entire cell, b) A 230 (115 * 2) mm length pusher*

Thinking after experiments

Both trials proved that the hydraulic press was sufficient for the pushing procedure, so no other proposals were made. The vertical push can successfully carry out the before and after procedures without additional transportation. Specifically, the hydraulic press pushes the battery in the battery holder, next the cell falls through the hole and then the unwinding procedure can start. In order to unwind the cell automatically, the hollow films in 13mm case should be clamped before the last cut step (as shown in Figure 30). The clamping position should be above the cutter.

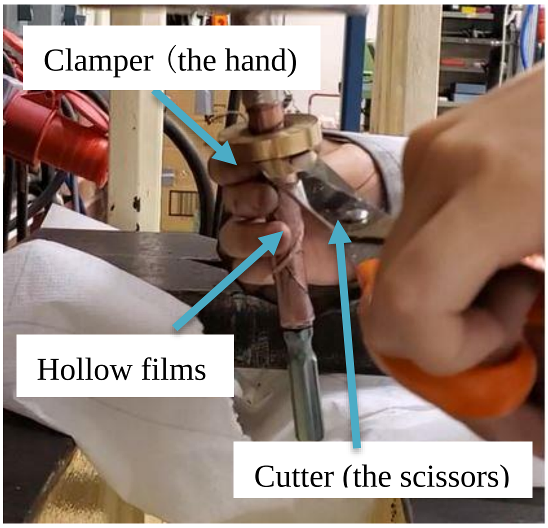


Figure 30 The tool combination

The 13mm pusher ends in a controllable clamped-edge which can be used in the upcoming unwinding procedure. In theoretical, 14 or 15mm should be the suitable size of a pusher because it can avoid tearing and might prove to be more efficient than 13mm pushers.

Both options in 13mm case may result in a torn cell during the pushing procedure. According to the author’s analysis, the possible reasons could be 1) mismatched joints and 2) the cell was constantly stretched during pushing.

In order to avoid a torn cell, 1) the pusher and the press should be designed in one-piece, for example a hydraulic press with 13mm press head, 2) the press head and the battery holder should be in the concentric position, 3) choose the actively cut off idea, the pushing time is shorter so that it reduces the possibility of generating an uneven edge.

However, the 13mm proposal requires further experiments to analyze other possibility that may lead to a tore cell. So far it is hard to promise the 13mm proposal works all the time. Therefore, the 16mm proposal is kept as the back-up plan.

After the pushing procedure:

Housings have been emptied and can be recycled after the pushing procedure, it can be further separated from plastic shells by density difference.

3.5 Procedure three: cell unwinding

3.5.1 Manual procedure

The unwinding procedure required a stick to drive the cell unwinding as Figure 31. A 3mm stick penetrated the center of the cell and held the cell firmly. When the stick rotated, it drove the cell rotating. This procedure should be assisted by two hands, one was in charge of moving the stick linearly while rotating, and another hand was used to catch the edge.

Figure 31 A 3mm stick hold the cell firmly

Thinking after experiments

In order to build an automated process, the functions of two hands should be replaced by some fixtures.

The stick can combine with a motor to achieve moving linearly while rotating automatically. In order to ensure the stick can pass through the cell automatically, the stick should be composed of two parts, a 2mm telescopic stick (the upper part) and a 3mm holding stick (the lower part). Specifically, before the pushing step, the telescopic part penetrates the center of the cell, and then the pushing step drives the cell falling down until it is fixed by the holding stick. The example model of this stick can be found in Appendix B a).

The function of the other hand has been achieved in the 13mm pusher case, the edge got clamped before the last cut step. For the torn cell case, the main problem is to catch the uneven edge.

The initial position of the stick. The stick and the battery holder should be in the concentric position.

Center Pin. A part of batteries has center pins in the middle of the cells, it does not have a good idea to automate this step, the current suggestion is to do the penetration step manually.

The distance of movement. According to Table 1, the length of anode and cathode foils are 53.7mm and 52 mm, respectively, so theoretically the linear movement should be 50mm. However, films have been cut and torn in the previous procedures, the practical distance should be checked in further testing.

3.5.2 Proposal 1: unwinding stick for the clamped edge

Since the stick has been passed through the cell and the edge has been clamped, the stick starts rotating until the entire cell unfolds.

3.5.3 Proposal 2: unwinding stick for the uneven edge

The same stick is used here but the uneven edge has not been clamped from previous procedures. An adhesive on the workbench can be used for cell unwinding. Since the unwinding procedure is ready, the stick rotates 90 degrees to lay the cell flat and then it moves down to the adhesive. Next, the anode foil (the outermost film) gets adhered on the adhesive. In the end, the stick moves linearly while rotating along with the adhesive until the entire cell unfolds.

This proposal has been proved in experiments, the adhesive was used double-sided type as Figure 32 shows. The procedure is shown in Figure 33.

Figure 32 Double-Sides tape from brand "Tesa" [28]

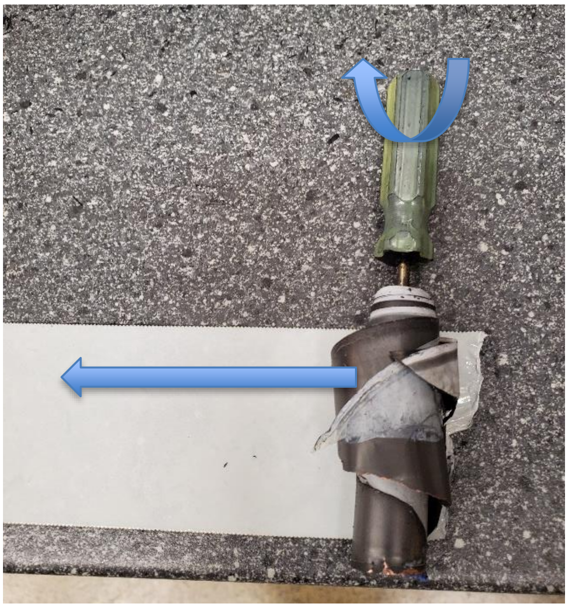


Figure 33 Use an adhesive to support the unwinding procedure

The idea to replace adhesive. Since the adhesive is attached to the workbench at the beginning, there are two ideas for adhesive replacement.
A scraper and a glue gun. This idea is to use a liquid adhesive that can be easily ejected by a glue gun. In details, the glue gun spreads adhesive on the workbench after the used adhesive has been cleaned by the scraper.
Replaceable adhesive plate. The adhesive is put on a replaceable plate in advance. There is a conveyor on the workbench which is used to transport the plate. The plate moves to the acetone solution and gets recycled when the adhesive falls off. This idea needs to keep feeding plates.

3.5.4 **Proposal 3: uneven edge clamper**

An edge clamper is used to catch the uneven edge. This proposal also needs an unwinding stick to carry the cell but only the rotation function is required. Since the unwinding procedure is ready, the stick rotates 90 degrees to lay the cell flat. Then an edge clamper close to the cell and try to catch the uneven edge when the stick starts rotating. Once all four films have been caught, the clamper moves along the bench to unwind the cell. Appendix B b1) and b2) show the example model for this proposal.
However, this idea is stopped at the concept stage because of the following two problems. Firstly, even though the clamper just next to the cell, the uneven edge is still difficult to catch. Secondly, the clamper requires a sensor to check whether all the four films are caught, but the sensor makes this step complicated and time-consuming.

3.5.5 **Proposal 4: collection pipe**

This proposal is also designed for the uneven edge case. A collection pipe is used to carry the cell. An embedded roller is located on one side of the pipe, it is used to drive the cell rotating. On the opposite of the roller, there is a gap on the pipe that is used to

release unwound films. Appendix B c1) shows the example model.
When the cell drops into the pipe, this pipe rotates 90 degrees to lay flat the cell and set the embedded roller on the top. Next, the roller drives the cell rotating and the uneven edge releases through the gap. In the end, the entire cell has been expanded and falls on the workbench. Appendix B c2) shows the expected result for this proposal.
However, this proposal is also stopped at the concept stage because the uneven edge problem cannot be solved, and this proposal also requires a sensor to check films.

3.6 Procedure four: foil separation

3.6.1 Manual procedure

This procedure is to separate the anode/cathode foil. The separation can be easily performed by hand, one hand picks up one film, and another hand press other films. Due to only anode/cathode foils have electrode materials, it is unnecessary to separate all four films completely.
The adhesive that used in the uneven edge case can be used for the cell separation. Since the anode foil has been adhered, the next step is to pick up the cathode foil. In the experiments, the operator finished this procedure by picking up the first two films so that the cathode foil with a separator was placed in the hand and the anode foil with the other separator was on the adhesive.
Thinking after experiments
After this procedure, foils require further procedures to remove electrode materials, for example put foils in NMP solution. NMP has a high solubility for PVDF which can treat foils in batch size in order to separate foils and electrode materials. Then foils can be recycled, and electrode materials require further chemical processes for extract lithium, cobalt, nickel and so on. If the adhesive is used in this procedure, the anode foil should be infiltrated in acetone solution to remove the adhesive.
Exception: Aging batteries
Batteries that electrode materials slip from the anode/cathode foils are called aging battery. The problem is the separator gathers different electrolyte materials on different sides so that it mixes both anode and cathode materials. The procedure mentioned here is only working for the ordinary cell case. Therefore, the aging cells should be moved to another process since they have been checked out. Figure 34 shows an example when anode materials slip off.

Figure 34 An example of an aging battery

3.6.2 Proposal 1: vacuum suction for the uneven edge case

Since the cell has been expanded and the anode foil has been bonded on the adhesive, the first proposal is to use a vacuum suction (Figure 35) to separate the anode and cathode. The vacuum suction sucks on the films and then pull it apart. Next, the vacuum suction takes the cathode foil to the cathode recycling zone and the anode foil is moved to the acetone solution for dissolving the adhesive.

Figure 35 An example of the vacuum suction equipment [29]

The suction step. Because the cell was wound by four films, three different possibilities could happen after the suction step as Table 4 shows.

No.	Adhesive (copper foil)	Vacuum suction equipment (separator 2)
1	Separator 1	Aluminum foil
2	Separator 1 and Aluminum foil	/
3	/	Separator 1 and Aluminum foil

Table 4 Separation result analysis

The second possibility is unsatisfied since the anode and cathode foils are mixed. However, the chance that both foils were mixed was lower than 33% according to experiment results. The cathode foil had stronger viscosity for both separators compared to the anode foil. In details, the cathode lead was bonded by two pieces of tape and it was located in between the cathode foil (Figure 36), thereby this area gathered more electrolytes and made the cathode foil stick to both separators tightly.

Figure 36 The cathode lead is located in between the cathode foil

A color sensor. The problem that anode/cathode foils are mixed together can be solved by a color sensor. Specifically, the sensor recognizes different films by the color difference. The anode film is pure black due to the electrolyte materials are black (Figure 37). The cathode film has a piece of silver color in between the black because an aluminum piece is there (Figure 38). The color of the separator film is white (Figure 37).

When the suction step is done, the color sensor checks the left films on the adhesive and determines whether the suction was successful. If the cathode foil is still on the adhesive, the failure can be corrected by redoing the suction step.

The color sensor can also be used for detecting the aging battery since the colors of the anode (copper foil) and cathode (aluminum foil) are distinctive.

Figure 37 Anode foil and separators in the ordinary case

Figure 38 Cathode foil in the ordinary case

3.6.3 Proposal 2: Two vacuum suctions for the clamped edge case

After the unwinding procedure, the films are still upright. Films have been expanded and the edge is still clamped. Next, two vacuum suctions move to both sides of the cell and suck the films at the same time. Next, the two equipment pull apart and then place anode/cathode foils to different recycling zones.

Issues of this proposal

Experiments found that the anode materials were not bonded tightly on the foil. The suction and pull apart steps may cause materials slip from the foil and further block the vacuum equipment, leading to malfunction. This proposal requires further testing to analyze the possibility of failure. The adhesive and single vacuum proposal can be the back-up plan.

3.6.4 Proposal 3: scrape off electrode materials

According to the observation from experiments, electrode materials especially the anode materials can be scraped off when foils are wetted. Specifically, sandpaper with 320 roughness and 80 roughness can scrape the anode and cathode material off (Figure 39) but the cathode foil may get damaged during this step. On the production scale, the sandpaper can be replaced by an automated brush.

Figure 39 Before and after using a 320 sandpaper on the anode (long)/cathode (short) foil

Issues of this proposal

Firstly, it needs water to infiltrate foils. According to section 2.5.3, $LiPF_6$ reacts with water and generates acidic and toxic products, so some extra steps are needed to clean up these products.

Secondly, the scraped off materials still requires a further procedure such as NMP solution to separate PVDF and electrode materials. Therefore, the scrape-off step is unnecessary. Besides, this idea has an unsatisfactory result on the cathode foil, which means it is a bad proposal for the cathode material recycling process.

Thirdly, electrode materials are bonded on both sides of the anode/cathode foil but the step for flipping over each film is difficult to realize.

3.7 Summary

Figure 40 shows the entire pre-treatment process which includes the required tools, the recyclable materials, the required detection steps and fault corrections. This process firstly separates the cell and the battery housing, next unwinds the cell and then separates the anode and cathode foils. In the end, different foils are placed in different recycling zones.

The propose of this process is to separate the anode/cathode foils thereby to recycle anode/cathode electrode materials separately. Because this process is a mechanical process, the separated anode/cathode foils require further chemical processes. This process cannot handle the aging batteries because both electrode materials are mixed on the separator. When they have been detected, the aging films should be moved to another process for further handling.

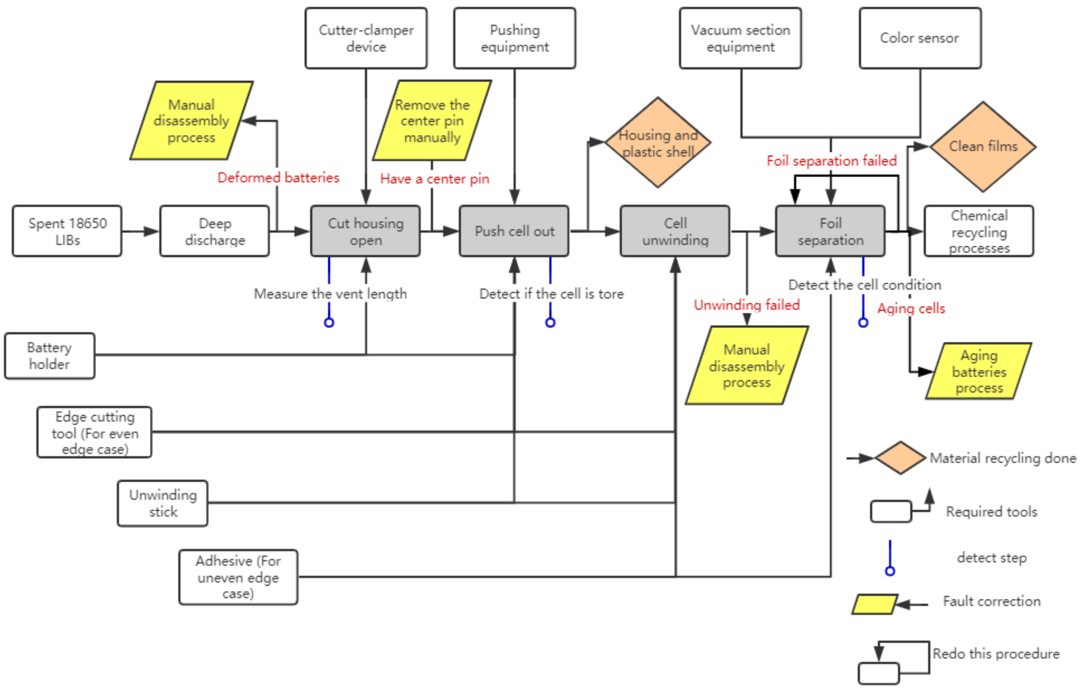


Figure 40 Pre-treatment process

4 Results

This chapter will integrate four procedures to a complete process and analyze the required time for each step. The solution in this chapter is based on the experiment results and thinking during the entire project, it is a principle solution which means it has not been verified or validated in practical. In the end, this solution is compared to other existing methods.

4.1 Cut housing open

The battery holder proposal has been selected.

The clamper in this procedure needs to catch the discharged battery from the LIBs zone to the battery holder. The coordinates of both areas should be recorded in the console system, then the clamper moves to the corresponding position and performs the picking action.

In order to pick and clamp batteries easily, a cylindrical holder/clamper is used for both the battery holder (Figure 41) and the clamper (Figure 42). This clamper consists of two half-piece cylinders which can hold the battery by surrounding the periphery of the housing. The height of this holder/clamper is half-length of batteries so that single clamper can perform picking and holding actions but couple can prevent battery damage during cutting and pushing step. The clamper-cutter tool performs several movements but all of them are easy to realize.

In this procedure, the battery requires to be flipped once so that the cell should be rotated in the counter-clockwise direction for unwinding.

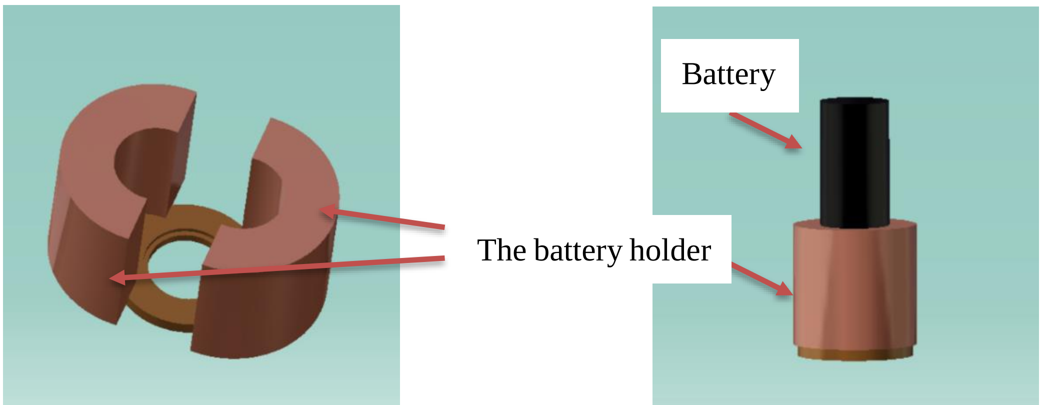


Figure 41 The new battery holder only holds half of the battery

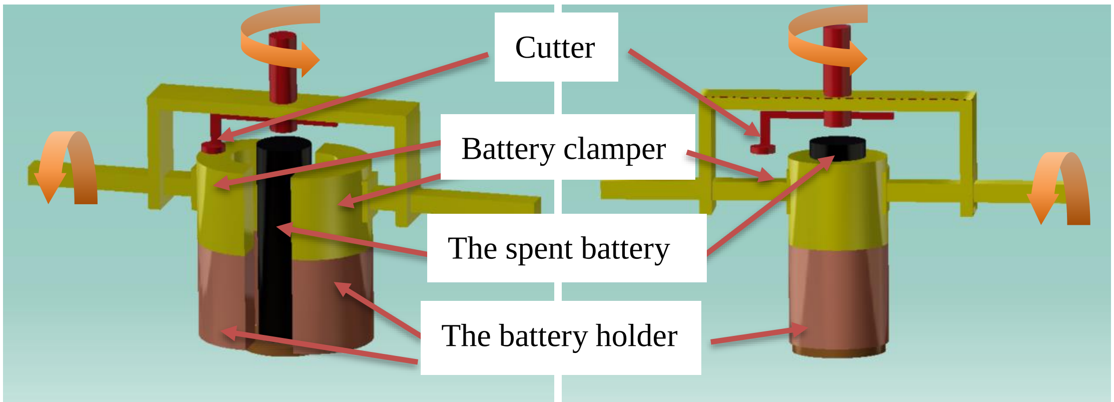


Figure 42 Clamper with a cutter tool

Table 5 estimates time consumptions in this procedure:

Action	Time (s)
Move the clamper to LIBs zone	1
Catch a LIB	1
Move the LIB to the battery holder	2
Holder clamps the battery	0.5
Cutting tool movement	0.5
Cut the top edge	1
Holder releases the battery	0.5
Clamper lifts, flips and puts down the battery	2.5
Holder clamps the battery	0.5
Cut bottom edge	1
Clamper releases the battery and moves away	1
Total	11.5

Table 5 Cut housing open procedure

4.2 Push cell out

This procedure is as same as the experiments in section 3.4, but the equipment should have a 13mm/16mm press head. The unwinding stick penetrates the cell before the pushing step.

According to experiment results, the required pushing force is over 1000 N, so the pushing equipment should be a heavy and unmovable equipment. In order to avoid the interfere between the clamper-cutter tool and the pushing equipment, the battery holder is designed movable.

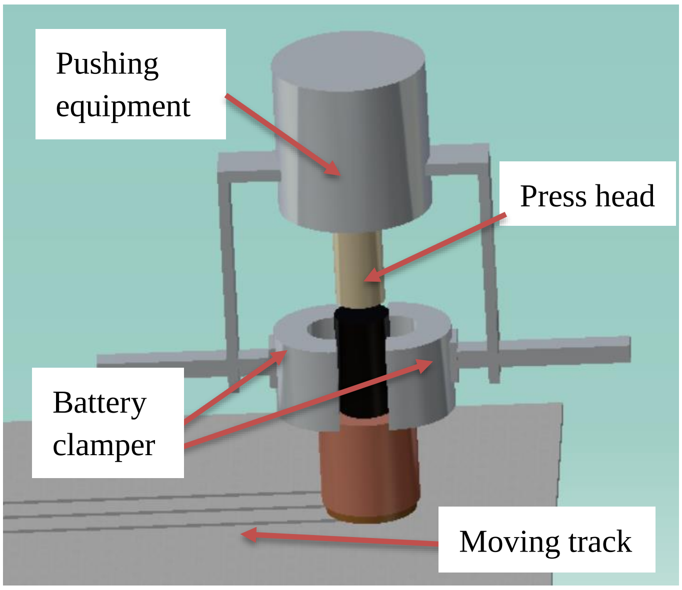


Figure 43 The pushing equipment

Since the battery holder has been changed to clamp only half of the battery, the pushing equipment also requires a cylindrical clamper for the other half as Figure 43 shows. When the battery has been fixed, the press head goes down to the cell surface, simultaneously the unwinding stick (as shown in Figure 44) penetrates the cell center. Next the pushing equipment pushes out the cell slowly. The pushing force should be controlled uniform and stable and the speed should be slow and even for avoiding battery damaging and preventing fire/explosion hazards. In the uneven edge case, the cell has been separated from the housing after pushing. In the clamped-edge case, an edge-cutting tool which combines cutter and clamper (as shown in Figure 45) is in charge of clamping the hollow films and cutting off the connection, then the cell continues to the unwinding procedure.

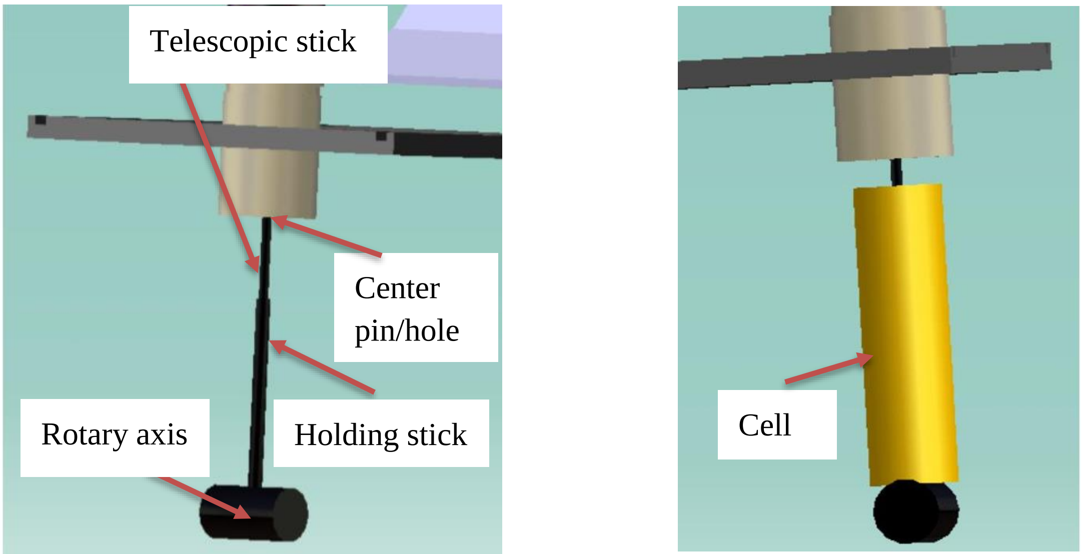


Figure 44 Details of the unwinding stick

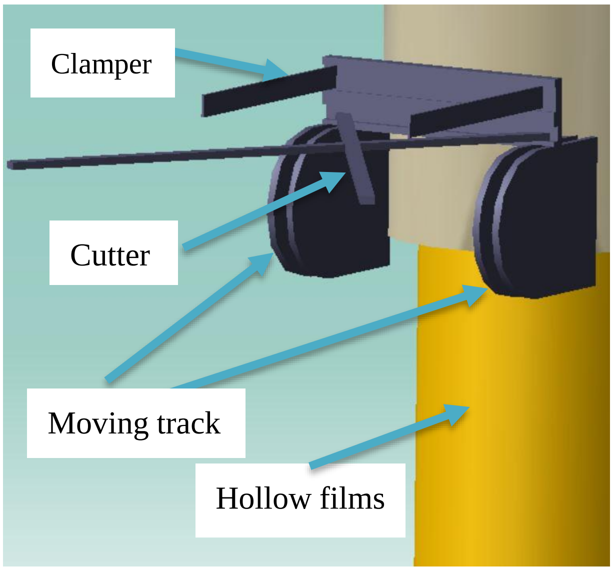


Figure 45 Edge cutting tool

Table 6 estimates time consumptions in the cell pushing procedure:

Action	Time (s)
Battery holder moves to pushing position	0.5
Move the clamper to the holder	1
The pushing device clamps the battery	0.5
Move the press head to the cell surface/ Unwinding stick penetrates the battery center	1
Push the cell out	4
Clamp and cut the connection (only in the clamped-edge case)/ Take out the pusher	1 / 2
Release the pushing device's clamper/ Release battery holder	1
Put the housing to the recycle zone/ Battery holder moves back to original position	0.5
Total	10.5

Table 6 Push cell out procedure

4.3 Cell unwinding and foil separation

The solution for this procedure has been separated to uneven edge and clamped-edge. It should be noted that the battery has been flipped once in the cut housing open procedure, so the unwinding should be performed in a counter-clockwise direction.

4.3.1 **Uneven edge case**

In the uneven edge case, the anode foil adheres on the adhesive, then the unwinding stick rotates to unwind the cell. Next, a vacuum suction sucks on the expanded cell and then pull it apart. Afterwards, the separation result is checked by a color sensor. It should be noted that only ordinary batteries that have been successfully separated can be placed in the anode/cathode recycling zone, the aging battery should be sent to another processing steps. Since the above steps have done, the upcoming procedure is to separate electrode materials by infiltrating foils in the NMP solution. Anode foils need to remove the adhesive by infiltrating in the acetone solution first. Figure 46 and Figure 47 shows the unwinding and foil separation procedures in the uneven edge case.

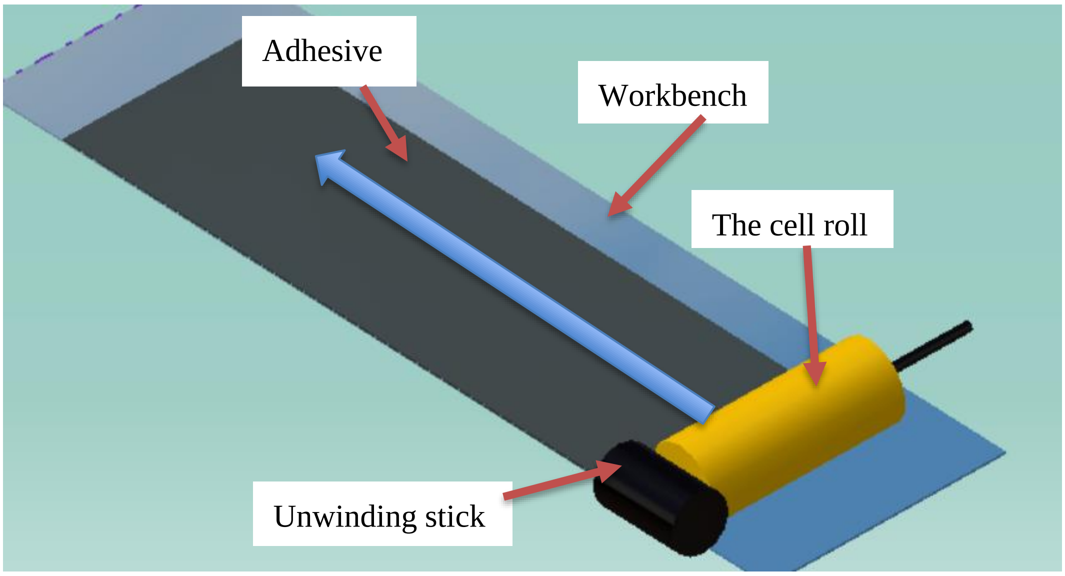


Figure 46 Unwinding procedure: uneven edge case

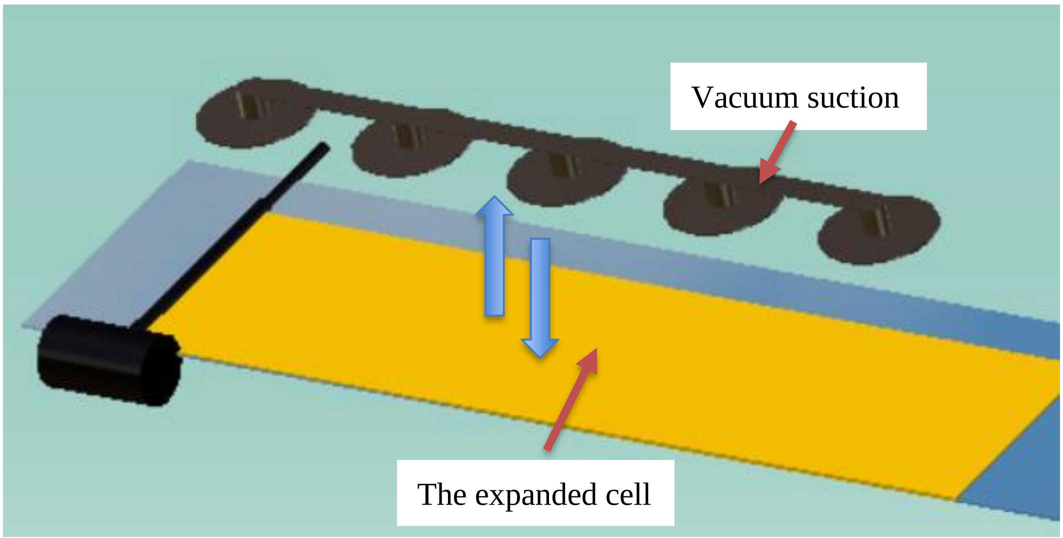


Figure 47 Foil separation: uneven edge case

Table 7 estimates time consumptions in the uneven edge case:

Action	Time (s)
Lay flat the cell roll	0.5
Move the unwinding stick attach to the adhesive	0.5
Rotate and move the unwinding stick until the entire cell expanded	3
Move suction equipment to films	1
Suction	0.5
Pull apart the suction equipment	1
Foil recognition/ Move unwinding stick back to the original position	2
Move suction equipment to cathode recycling zone/ remove the adhesive and replace a new one	1.5
Move suction equipment back to the original position	1
Total	11

Table 7 Unwinding and foil separation in uneven edge case

4.3.2 **Clamped-edge case**

In the clamped-edge case, the unwinding stick starts rotating to unwind the cell first. Since the cell has been expanded, two vacuum suctions suck on both side of the cell and pull them apart. Next, the separation result is checked by a color sensor. As it mentioned before, the aging batteries should be separated from other ordinary batteries. In the end, the collected anode/cathode foils infiltrates in the NMP solution to separate electrode materials from foils. Figure 48 and Figure 49 shows the unwinding and foil separation procedures in the clamped-edge case.

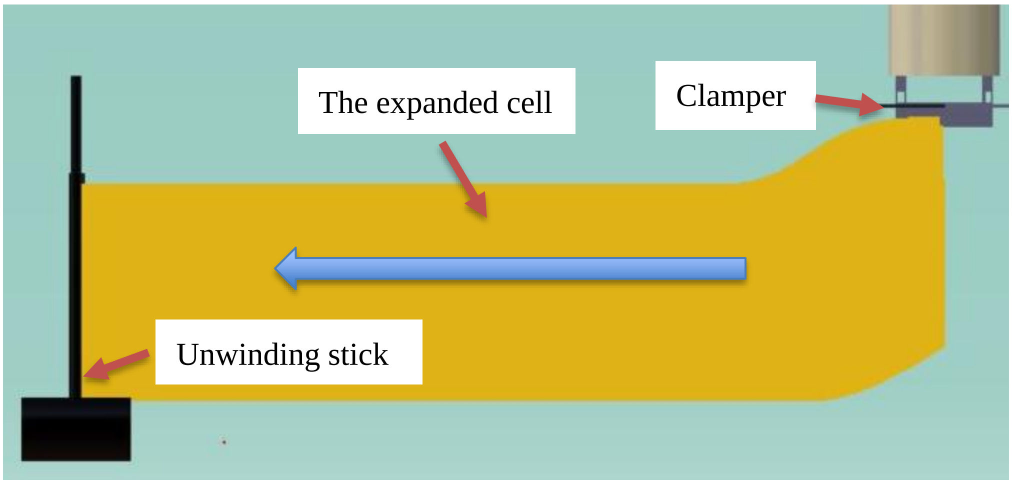


Figure 48 Unwinding procedure: clamped-edge case

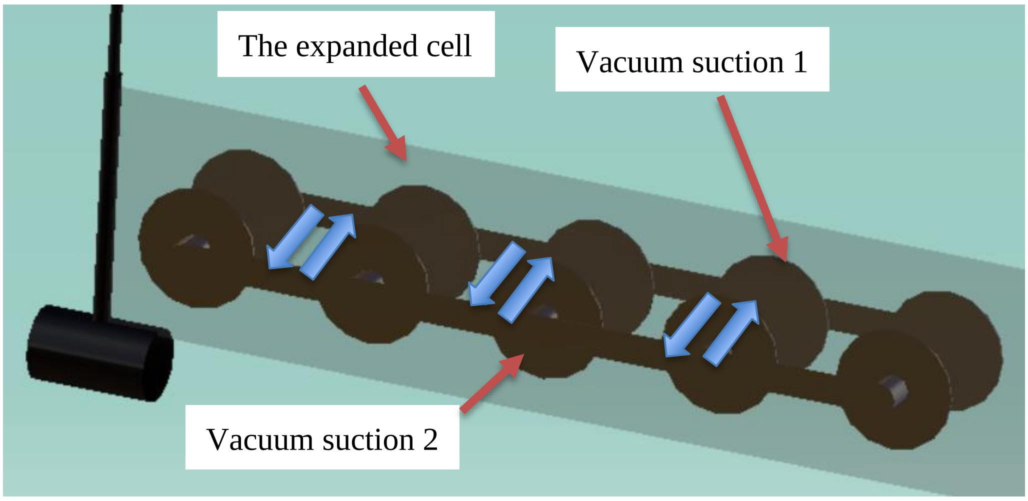


Figure 49 Foil separation: clamped-edge case

Table 8 estimates time consumptions in the clamped-edge case:

Action	Time (s)
Move and rotate the unwinding stick until the cell expanded	3
Move two suction equipment to both sides of films	1
Suction	0.5
Pull open the suction equipment/ move edge cutting tool back to original position	1
Foil recognition/ Move unwinding stick back to the original position	2
Move suction equipment to cathode/anode recycling zone	1.5
Move suction equipment back to the original position	1
Total	10

Table 8 Unwinding and foil separation in clamped-edge case

4.4 Summary

4.4.1 The pre-treatment process

According to the previous analysis, the entire pre-treatment process needs 11.5 seconds to disassemble one battery. Figure 50 shows the time consumption in each procedure.

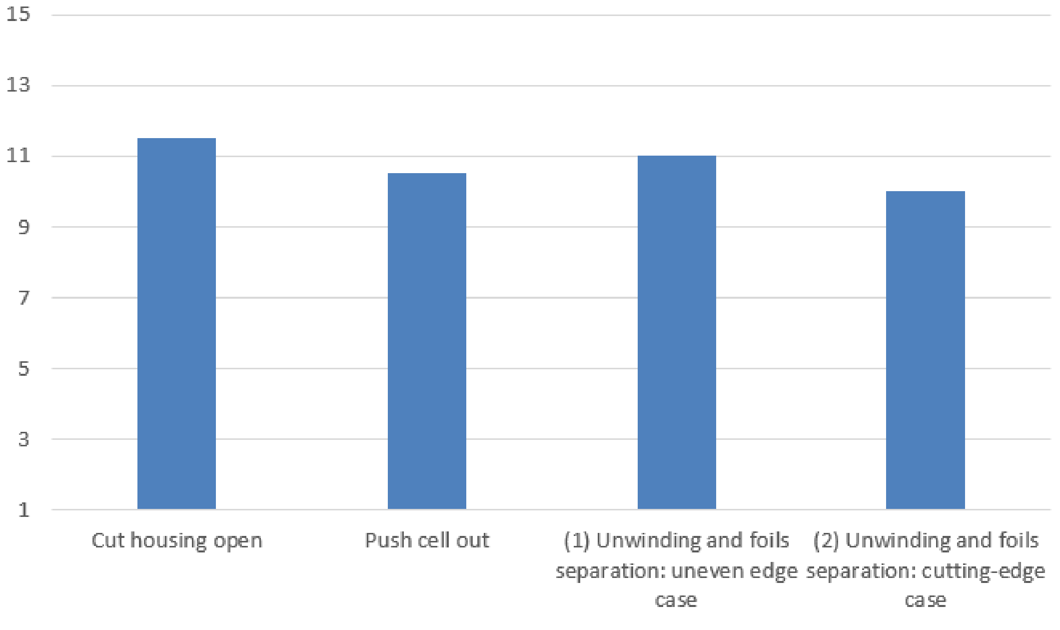


Figure 50 Time consumption in each procedure

Assume this production flow works 8 hours a day and has one shift, the OEE (Overall Equipment Effectiveness) of this production line has been assumed as 80%. The number of recycled batteries in a single day is shown in the equation:

$$Recycled\ batteries/day = \frac{working\ time\ in\ seconds * shifts * OEE}{seconds\ for\ one\ battery\ recycling}$$
$$= \frac{8 * 3600 * 1 * 80\%}{11.5} = 2003.48 \approx 2003$$

Take Tesla Model S as an example, this production line needs 3.6 workdays to complete the disassembly of 7104 pieces batteries.

Section 2.3.1 has mentioned that the lifecycle of electric cars is around 15 years. According to the statistics of sold Tesla in Table 2, there are around 1300 Tesla cars need to be recycled in 2033 in Sweden. Assume that a recycling factory works 40 hours a week with one shift, the machines' OEE is 80%. If this is the only factory in Sweden, the daily increment of cars is shown in the equation:

$$Daily\ increment\ in\ 2033 = \frac{Sold\ Tesla\ in\ 2018}{days\ in\ a\ year} = \frac{1300}{365} = 3.56 \approx 4$$

In order to recycle these discarded batteries in time (assume all the cars are Tesla Model S), the required production lines are:

$$Required\ production\ line = \frac{Sold\ Tesla\ in\ 2018 * batteries\ in\ Model\ S}{the\ capacity\ of\ one\ production\ line\ in\ one\ day * working\ days\ for\ a\ year} = \frac{1300 * 7104}{2003.48 * 5 * 52} = 17.72 \approx 18$$

This factory needs 18 production lines to handle the daily increment and avoid batteries hoarding problem in 2033.

4.4.2 Comparison with other approaches

This work proposes a principle recycling solution for 18650 battery disassembly. It is mainly focused on getting the cell out and then separating the anode and cathode foils. The mechanical method is hard to separate the electrode materials and foils, so this work should further continue to other chemical processes in order to recycle cobalt, lithium, nickel and so on. This solution is achieved to execute the pre-treatment process in an automated way. The entire process is continuous and no manual transportation is required in the middle. However, it does not have a good solution for removing center pins and the aging batteries should be separated from other ordinary batteries. In the current situation, it suggests doing these two things manually.

The following comparison is only focused on the pre-treatment process. According to section 2.4, the two most common approaches are disassembling batteries manually and incineration. Compared with the manual approach, the new approach can treat batteries on batch-scale in an automated way. Compared with the incineration approach, the new one can save more materials but does not generate extra pollutions. Therefore, this work found a compromise solution. Table 9 shows the comparison results:

Method	Success rate	Recycled materials	Effectiveness	pollution	Production requirements
Manual	100%	++++	-	+	/
Incineration	100%	+	++++	++++	++++
16 mm pusher idea	100% (ideally)	++	++	+	++
13 mm pusher idea	70% (ideally)	+++	++	+	++

Table 9 Methods comparison

5 Battery design suggestion

There are some suggestions for simplifying the future battery disassembly process based on thinking during the entire project.

1) **Establish a vehicle LIB standard:** According to the observation during disassembly experiments, the 18650 standards only specify the battery size, but the differences in details hinder the recycling process. For example some cells do not have center pins, or the lengths of the safety vents are different. The suggestion for simplifying this process is to avoid using center pins but make the center hollow. Moreover, if a battery standard can specify every detail of the battery and all products are produced to this standard, then the recycling line does not need to change parameters between different batteries.
2) **Change the design of LIB packs fixture:** A LIB pack arranges batteries in orders and sets each battery in fixed positions that can be used as an advantage. Batteries can be picked according to fixture grids (Figure 51). However, the current fixtures are hard to disassemble which obstructs this idea.

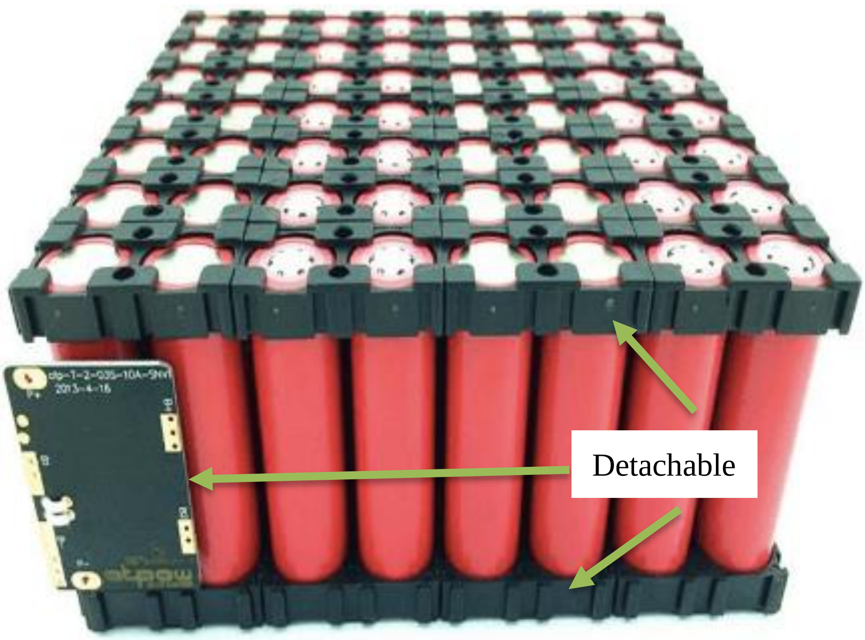


Figure 51 The ideal LIB pack design [30]

3) **Add magnetic bar at the anode/cathode foil:** The cell is composed of four films but only copper and aluminum foils have electrode materials. Especially the cathode materials are much valuable than others. The suggestion is to add a magnetic bar on the cathode (and anode) foil so that it can easily select the cathode/anode foil by magnetics
4) **Change the seal solution:** In the current battery design, cells get damaged during the cutting procedure. A suggestion is to use a bottle cap sealing solution to avoid cutting. Since the bottle sealing technique also can prevent gas and liquid leakage, this idea is ideally possible to apply to batteries. Figure 52 shows a sealing solution

from Enercon.

Figure 52 The Enercon cap sealing solution [31]

6 Conclusion

This work led to the following conclusions:

1. This work proposed a principle solution for the pre-treatment process which included the procedures from taking the cell roll out to separating the anode/cathode foil. The solution was a mechanical process so that the recycling of cobalt, lithium and nickel were required further hydrometallurgical or bioleaching approaches.
2. This solution was designed for the 18650 type battery, other type batteries and deformed batteries cannot be produced in this process. The current solution cannot solve the center pin and aging batteries problems. The center pin should be removed by manual operation and aging batteries need to be moved to another process for further treatment. Chapter 5 mentioned several ideas for battery design in order to simplify the disassembly process.
3. Section 2.5 had mentioned several hazards that may happen during the disassembly process, the safety measures should be considered before the implementation of the production line.
4. The 13 mm pusher and the two vacuum suctions' idea deserve further tests, the author thinks that these two ideas are better because the clamped-edge can simplify unwinding and foil separations procedures. According to the experiment results, the adhesive idea can handle both uneven edge and clamped-edge cases. If further tests prove that these two ideas are defective, the adhesive idea can be used as the back-up plan

7 References

[1] T. Elwert, F. Römer, K. Schneider, Q. Hua, and M. Buchert, ‘Recycling of Batteries from Electric Vehicles’, in *Behaviour of Lithium-Ion Batteries in Electric Vehicles: Battery Health, Performance, Safety, and Cost*, G. Pistoia and B. Liaw, Eds. Cham: Springer International Publishing, 2018, pp. 289–321.

[2] ‘About the Group’, *Stena Metall English*. [Online]. Available: https://www.stenametall.com/stena-metall-group/about-the-group/. [Accessed: 31-Jan-2019].

[3] D. P. Mantuano, G. Dorella, R. C. A. Elias, and M. B. Mansur, ‘Analysis of a hydrometallurgical route to recover base metals from spent rechargeable batteries by liquid–liquid extraction with Cyanex 272’, *J. Power Sources*, vol. 159, no. 2, pp. 1510–1518, Sep. 2006.

[4] S. Leuthner, ‘Lithium-ion battery overview’, in *Lithium-Ion Batteries: Basics and Applications*, R. Korthauer, Ed. Berlin, Heidelberg: Springer Berlin Heidelberg, 2018, pp. 13–19.

[5] H. Yu and H. Zhou, ‘High-Energy Cathode Materials (Li2MnO3–LiMO2) for Lithium-Ion Batteries’, *J. Phys. Chem. Lett.*, vol. 4, no. 8, pp. 1268–1280, Apr. 2013.

[6] M. Grützke *et al.*, ‘Aging investigations of a lithium-ion battery electrolyte from a field-tested hybrid electric vehicle’, *J. Power Sources*, vol. 273, pp. 83–88, Jan. 2015.

[7] M. Contestabile, S. Panero, and B. Scrosati, ‘A laboratory-scale lithium-ion battery recycling process’, *J. Power Sources*, vol. 92, no. 1, pp. 65–69, Jan. 2001.

[8] Y. Lu, Q. Zhang, and J. Chen, ‘Recent progress on lithium-ion batteries with high electrochemical performance’, *Sci. China Chem.*, vol. 62, no. 5, pp. 533–548, May 2019.

[9] Y. Liu and M. Liu, ‘Reproduction of Li battery LiNixMnyCo1−x−yO2 positive electrode material from the recycling of waste battery’, *Int. J. Hydrog. Energy*, vol. 42, no. 29, pp. 18189–18195, Jul. 2017.

[10] ‘Polyvinylidene Fluoride (PVDF) Plastic: Material Properties & Other Info’. [Online]. Available: https://omnexus.specialchem.com/selection-guide/polyvinylidene-fluoride-pvdf-plastic. [Accessed: 13-Aug-2019].

[11] L. Li *et al.*, ‘Ascorbic-acid-assisted recovery of cobalt and lithium from spent Li-ion batteries’, *J. Power Sources*, vol. 218, pp. 21–27, Nov. 2012.

[12] C. Pillot, ‘Lithium ion battery raw material Supply & demand 2016-2025’, p. 43, 2017.

[13] ‘Tesla European sales figures’. [Online]. Available: http://carsalesbase.com/european-car-sales-data/tesla/. [Accessed: 24-Aug-2019].

[14] T. Georgi-Maschler, B. Friedrich, R. Weyhe, H. Heegn, and M. Rutz, ‘Development of a recycling process for Li-ion batteries’, *J. Power Sources*, vol. 207, pp. 173–182, Jun. 2012.

[15] G. Dorella and M. B. Mansur, ‘A study of the separation of cobalt from spent Li-ion battery residues’, *J. Power Sources*, vol. 170, no. 1, pp. 210–215, Jun. 2007.

[16] C. K. Lee and K.-I. Rhee, ‘Reductive leaching of cathodic active materials from lithium ion battery wastes’, *Hydrometallurgy*, vol. 68, no. 1, pp. 5–10, Feb. 2003.

[17] S. M. Shin, N. H. Kim, J. S. Sohn, D. H. Yang, and Y. H. Kim, ‘Development of a metal recovery process from Li-ion battery wastes’, *Hydrometallurgy*, vol. 79, no. 3, pp. 172–181, Oct. 2005.

[18] L. Li, J. Ge, R. Chen, F. Wu, S. Chen, and X. Zhang, ‘Environmental friendly leaching reagent for cobalt and lithium recovery from spent lithium-ion batteries’, *Waste Manag.*, vol. 30, no. 12, pp. 2615–2621, Dec. 2010.

[19] J. F. Paulino, N. G. Busnardo, and J. C. Afonso, ‘Recovery of valuable elements from spent Li-batteries’, *J. Hazard. Mater.*, vol. 150, no. 3, pp. 843–849, Feb. 2008.

[20] B. Xin *et al.*, ‘Bioleaching mechanism of Co and Li from spent lithium-ion battery by the mixed culture of acidophilic sulfur-oxidizing and iron-oxidizing bacteria’, *Bioresour. Technol.*, vol. 100, no. 24, pp. 6163–6169, Dec. 2009.

[21] D. Mishra, D.-J. Kim, D. E. Ralph, J.-G. Ahn, and Y.-H. Rhee, ‘Bioleaching of

metals from spent lithium ion secondary batteries using Acidithiobacillus ferrooxidans', *Waste Manag.*, vol. 28, no. 2, pp. 333–338, Jan. 2008.

[22] J. Diekmann *et al.*, 'Potential Dangers During the Handling of Lithium-Ion Batteries', in *Recycling of Lithium-Ion Batteries: The LithoRec Way*, A. Kwade and J. Diekmann, Eds. Cham: Springer International Publishing, 2018, pp. 39–51.

[23] R. Si, D. Liu, and S. Xue, 'Experimental Study on Fire and Explosion Suppression of Self-ignition of Lithium Ion Battery', *Procedia Eng.*, vol. 211, pp. 629–634, Jan. 2018.

[24] P. Haas, S. Pfeifer, J. Müller, C. Bradtmöller, and S. Scholl, 'Separation of the Electrolyte—Solvent Extraction', in *Recycling of Lithium-Ion Batteries: The LithoRec Way*, A. Kwade and J. Diekmann, Eds. Cham: Springer International Publishing, 2018, pp. 155–176.

[25] 'Battery Separators: How can the plastics industry meet current challenges?' [Online]. Available: https://omnexus.specialchem.com/tech-library/article/battery-separators-how-can-the-plastics-industry-meet-current-challenges. [Accessed: 13-Aug-2019].

[26] 'Hydraulic Press Automatic (h Frame)', *indiamart.com*. [Online]. Available: https://www.indiamart.com/proddetail/hydraulic-press-automatic-h-frame-15267367412.html. [Accessed: 28-Aug-2019].

[27] 'BESSEY 5 in. Drop Forged Bench Vise with Swivel Base-BV-DF5SB', *The Home Depot*. [Online]. Available: https://www.homedepot.com/p/BESSEY-5-in-Drop-Forged-Bench-Vise-with-Swivel-Base-BV-DF5SB/301233421. [Accessed: 28-Aug-2019].

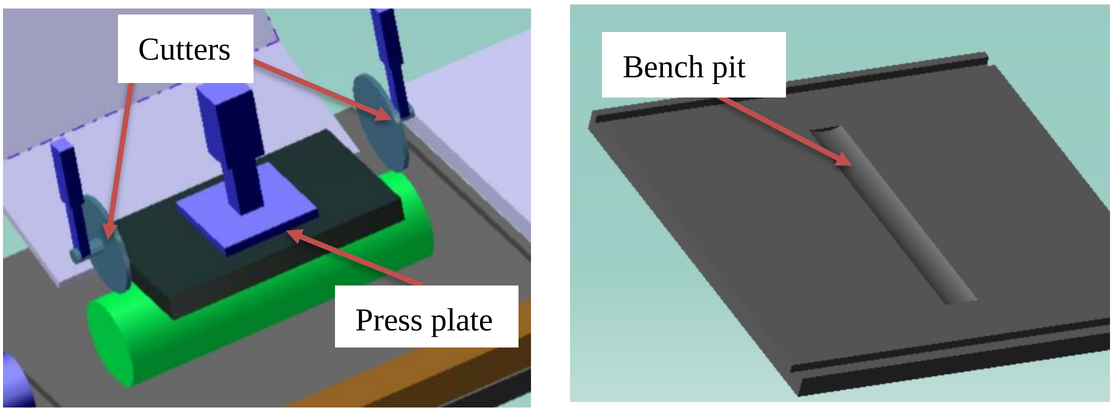
[28] 'Double-Sided Adhesive Tapes'. [Online]. Available: https://www.tesa.com/en/wikitapia/double-sided-adhesive-tape. [Accessed: 04-Sep-2019].

[29] 'Vacuum Systems For Successful Robot Implementation | RoboticsTomorrow'. [Online]. Available: https://roboticstomorrow.com/article/2013/10/vacuum-systems-for-successful-robot-implementation/206. [Accessed: 04-Sep-2019].

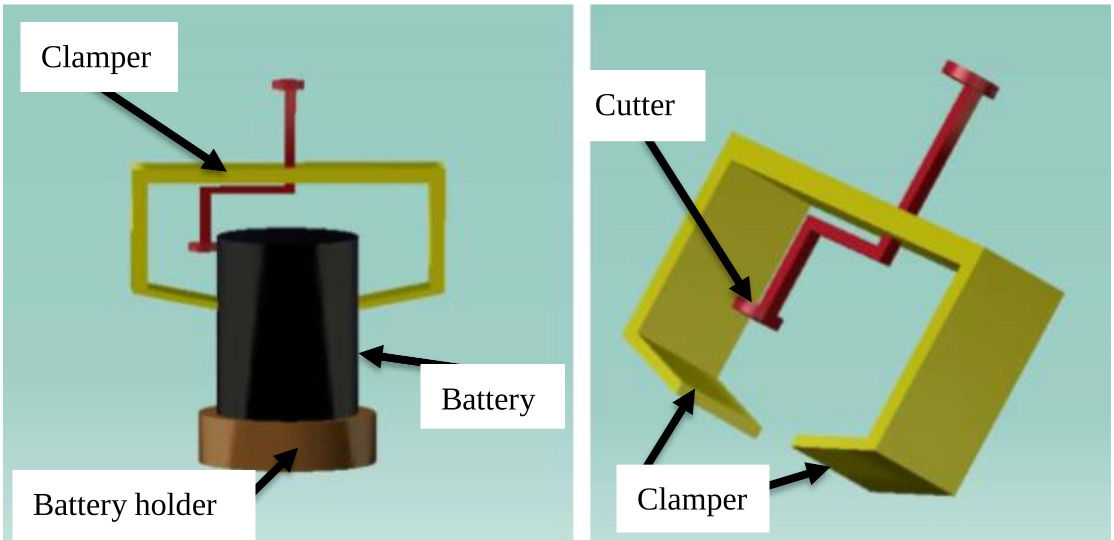
[30] D. T. P. Battery, '36V 18650 battery pack', *Supply whole battery pack solutions*. .

[31] 'Induction Sealing Machines & Equipment: Cap Sealer System - Enercon Industries'. [Online]. Available: https://www.enerconind.com/sealing/cap-sealers.aspx. [Accessed: 31-Aug-2019].

Appendix A

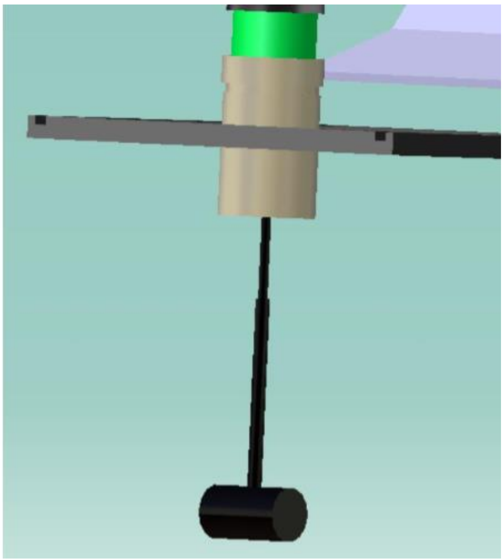


a) *Proposal 1: bench pit and press plate*

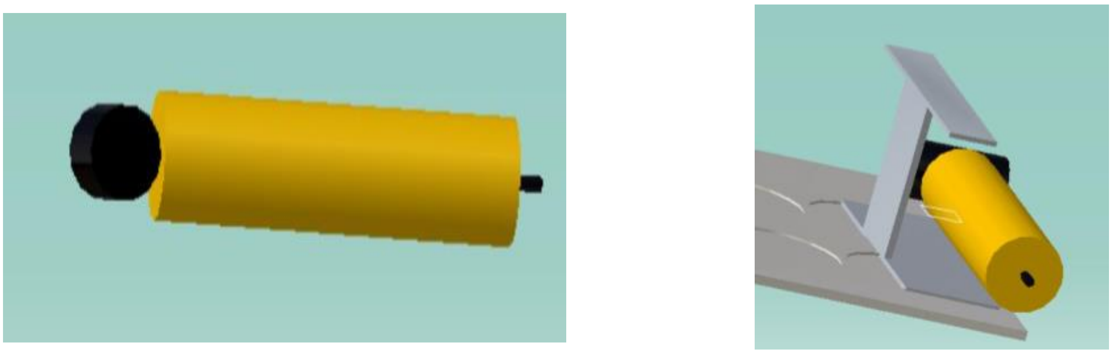


b) *Proposal 2: battery holder and cutter-clamper*

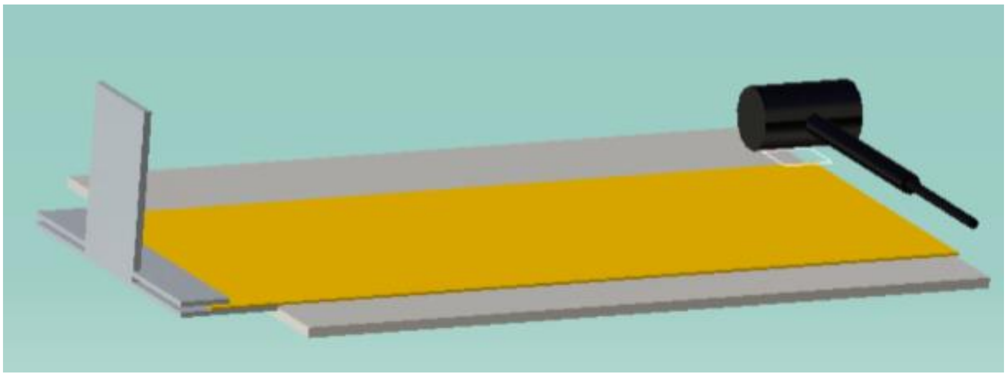
Appendix B



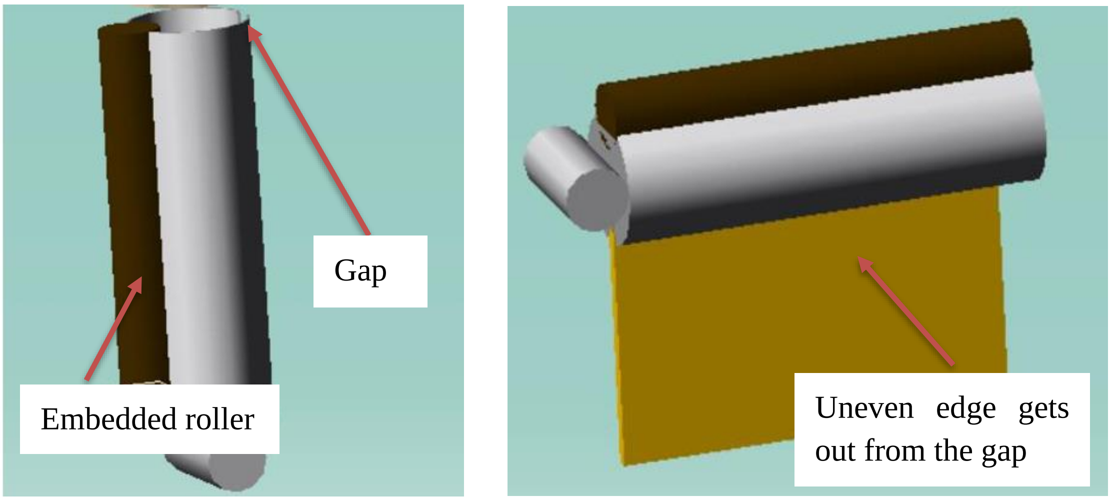
a1) The unwinding stick



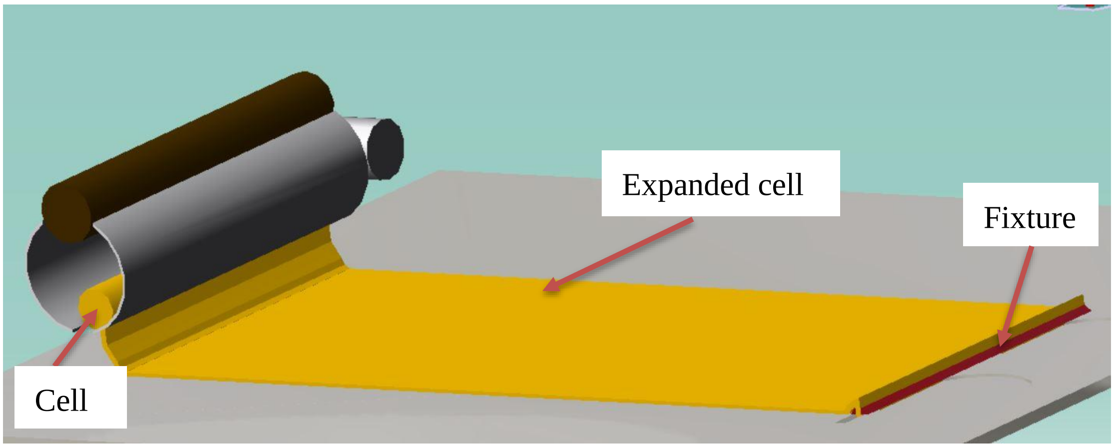
b1) Proposal 3: uneven edge clamper



b2) Proposal 3: the result after this procedure



c1) Proposal 4: the collection pipe



c2) Proposal 4: the result after this procedure