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Analysis of the Variety of Lithium-Ion Battery Modules and the Challenges for an Agile Automated Disassembly System

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Abstract

Within this paper the initial steps for the realisation of an agile automated system for battery module disassembly will be presented. The state of the art battery modules need to be analysed with regards to their structure, components and the relationship of the components to each other. In particular, the key challenges in battery module disassembly up to cell level are identified and classified in order to systematically derive the requirements for the disassembly system. The identified challenges for automated disassembly are twofold: process-related and product-related. The variety of battery modules can be seen as a product-related challenge, while non-detachable joints combined with the hazards posed by Li-ion batteries can be described as process-related challenge. An approach for capturing the variety of battery modules is done by using the methodology of a morphological box.

Keywords: Disassembly; Manufacturing system; Separation of Non-Detachable Joints

1. Introduction

The automotive industry is undertaking a process of tremendous upheaval and major reorganization [1]. Stricter environmental regulations (e.g. new climate targets such as the 2015 Paris Agreement [2] and growing environmental awareness are only one way of preventing scandals such as the "diesel exhaust affair" [3] and excessive pollutant emissions. For more than a decade, the search for alternative drive concepts has been unavoidable - with electric mobility leading the way. Consequently, the sales volume of electric vehicles has grown enormously [4]. Hereby, Li-ion batteries gained in market share during the past years [1], while on the same time questions regarding disassembly at end of life (EOL) scenarios including remanufacturing, recycling and the sustainable usage of scarce raw materials occurred [5]. The exiguity of a circular economy and value recovery from EOL products can be achieved by three substantial proceedings: reusing, remanufacturing and recycling [6]. Products that are in a good condition can be reused, while inoperable products may need to be remanufactured or recycled [6]. For this purpose, disintegration including disassembly and shredding can be carried out in dependence of technological and economic aspects. While disassembling presents a method for systematically separating a product into e.g. its sub-components, shredding presents a destructively method of breaking down the product into smaller pieces [6]. So far, the vast number of electric vehicle suppliers and large variety of battery modules hinders a standardized utilization of automated disassembly concepts. Currently, Li-ion traction batteries are only disassembled down to a module level due to the lack of standardized battery modules [7, 8]. Afterwards, it is state of the art that the single modules are shredded because it would otherwise imply high economic costs when disassembling [9]. Nevertheless, the potential of increasing the disassembling granularity down to the cell level seems to be inevitable for a sustainable recycling of Li-ion batteries. Through disassembling Li-ion traction batteries into more granular structures, the purity of individual fractions increases and supersedes further recycling processes [6]. Furthermore, functioning components such as battery cells could possibly be remanufactured or utilized for second-use applications [10, 11].

This paper is addressing the disassembly step "battery module into cells", as there is still potential for economic automation. The overall goal is to achieve an agile disassembly system, which can adapt cost-efficiently to changes in the batch size as well as the variety of variants with different kind of joints

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through flexibility and reconfigurability, similar to an agile assembly system [12].

In particular, the focus of this paper is to systematically identify and classify the key challenges to take a step towards an agile automated disassembly system. The dismantling of battery modules is particularly accompanied by different challenges, whereby in the following a classification between product-related and process-related challenges is made. The vast variety of battery modules and their components can be named as a product-related challenge. Currently, there is no standardized design for battery modules, e.g. in the form of a norm [13]. The battery cell type is selected according to the customer standard, which ultimately influences the design of the battery module [14]. Scientific work regarding the development of standards for battery modules, e.g. [15], already exist but have not been fully implemented. The process-related challenge is posed by non-detachable joints combined with the dangers posed by Li-ion batteries. Non-detachable joints require destructive or partially destructive separation processes [16]. Due to the dangers posed by the Li-ion battery, only certain separation processes are suitable. The following approaches are used to address the two challenges described above: The variety of state of the art battery modules is captured by identifying similarities and differences referring to each component and using the methodology of a morphological box. Regarding the process-related challenges the non-detachable joints are identified, classified and the location between the battery module components is shown in a component-relationship-matrix (based on [17]). Furthermore, the hazards relevant for disassembly are identified in order to derive the requirements for the disassembly process. In the following, the fundamentals of Li-ion batteries are explained as well as the product- and process-related challenges are examined in more detail.

2. Fundamentals of Li-ion batteries

Li-ion batteries can be found in different areas and are used especially as traction batteries due to their advantages such as high power and energy density [18]. Further battery types like redox-flow- or metal-air batteries offer an enormous potential but are currently connected with challenges and therefore subject of current research [19].

The Li-ion traction battery can be divided into three hierarchical levels. The highest level is the battery system, which consists of battery modules. The modules are made up of individual cells that form the actual energy storage [20].

In general, Li-ion battery cells consists of the components anode, separator, cathode, an electrolyte, the current collectors as well as a housing [21]. The anode and cathode are made of active material coated on a thin metal foil. In the most common configuration, the anode consists of a copper foil with coated graphite and the cathode is an aluminum foil coated with $LiNi_xCo_yMn_zO_2$ [18]. The separator, which is only permeable for Li ions, separates the anode from the cathode. The electrolyte consists of a non-aqueous solvent (e.g. ethylene carbonate) and solution salt $LiPF_6$. The two collectors form an electrical contact to the metal foils of the respective electrodes and are electrically insulated from each other. During charging, the Li ions flow from the cathode (metal oxide) through the separator to the anode (graphite) and form an intercalation compound with the graphite. When discharging, the reverse process occurs. The electron flow takes place externally [18]. During charging/discharging and thus entry/exit of Li-ions into/from the graphite grid a change in volume of the grid occurs, which is expressed particularly in the form of a change in thickness of the battery cell [18]. This effect is known as cell respiration and should be taken into account especially in module design as well as assembly and disassembly due to the occurring mechanical tensions [22].

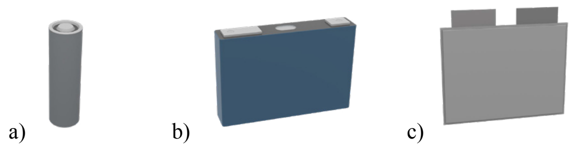

Fig. 1. a) cylindrical cell, b) prismatic cell, c) pouch cell

In principle, one differentiates between the cell types cylindrical, prismatic and pouch cells [18], which are illustrated in Fig. 1. The cylindrical and prismatic cells consist of a hard case (usually aluminum or stainless steel [23]) in which an electrode coil is inserted. The hard case is then welded. In pouch cells, the electrode stack, which is mainly produced by z-folding or stacking, is enclosed by a form-unstable pouch foil. The foil is polyamide-aluminum-polypropylene compound, which is closed by a heat-sealing process [23, 18]. In the following, the battery module is divided into its subsystems (components) from a disassembly point of view. The structure of a module is primarily dependent on the utilized cell type. Nevertheless, the following six components can be identified across all cell types (according to [20]): Battery cell, cooling system, cell contactor, Battery Management System (BMS), cell fixation and housing. A detailed description of each component can be found in the following chapter.

3. Product-related challenges

In this paper, a morphological analysis as a method to investigate the totality of all relations in multidimensional, mostly unquantifiable problems following Fritz Zwicky (1967) [24] was used in combination with a branching structure. The morphological box, as illustrated in Fig. 2, merges all Li-ion battery module components and their differentiating characteristics into one single model. Every battery module can be disassembled into the same six main components: battery cells, cell contacting, cell fixation, housing, thermal management and the BMS (including its periphery). When choosing a path, e.g. a prismatic cell, it is evident that some of the following paths are dependant of that particular choice. All decision branches are illustrated with bold lines on the side walls of the morphological box. Once a bold line is on the bottom, the tree branch ends, and the following path can be independently chosen. At

Components	*	Different. Properties	Manifestations					
battery cell		cell type	CYLINDRICAL	PRISMATIC	POUCH (with compression pads)			
battery cell		row	multiple rows	single-rowed	two-rowed	single-rowed		
battery cell		arrester position	opposite side	same side	same side	opposite side		
cell contacting			CYLINDRICAL	PRISMATIC	POUCH			
cell contacting	yes	connection type	adhesive bond	adhesive bond	traction/form fit	adhesive bond	traction/form fit	
cell contacting	yes	joining technology	welding	welding	screwing	welding	screwing	
cell contacting	yes	bridge	busbar <with bonding wires> (collector sheets)	busbar [tab-to-busbar]	hole-busbar [tab-to-busbar]	[tab-to-tab]	busbar [tab-to-busbar]	screw threads-/ hole-busbar
cell contacting	yes	support plate	no	yes	no	no	no	no
cell fixation			CYLINDRICAL	PRISMATIC	POUCH			
cell fixation	yes	primary fixation (cell-to-cell)	rigid spacer, spacer strip, mounting bracket (incl. recesses)	<gluing>	<gluing>	<cell frame>	<gluing>	
cell fixation	no	secondary fixation (cell-group)	non-detachable joined side panels	detachable joined end plates and/or side panels <with tension/stretch unit>				
modul housing	-	function-integration in cell fixation	yes	no				
modul housing	no	amount of individual parts		one-part	two-part	multipartite		
modul housing	no	joining type of individual parts		detachable joined	non-detachable joined			
thermal management	no	cooling types	air cooling	fluid cooling				
thermal management	no	types		floor/head cooling	side cooling	arrestor cooling	cooling plate (fluid)	heat-conducting plate
BMS & periphery	no	topology	centralized (all units integrated within master)	master/slave, PMU & MMU integrated within master	master/slave, MMU & CMU integrated within slave	distributed software BMS		
			Legend	< > optional element	* battery cell dependency	[ ] technical expression		

Fig. 2. Morphological box with manifestation of the battery modul components

this point, it should be mentioned that there is no guarantee of completeness since there is a rapid development in electric mobility research and furthermore, the car manufacturers and sub supplier only provide a limited access to information. Nevertheless, the following subparagraphs investigate the main components in more detail and approach of systematically capture trends and tendencies for an overall overview.

3.1. Battery cell types

As described in chapter 2, Li-ion battery cells can be subdivided into the three cell types. Apart from the cell types, Li-ion battery cells can be further differentiated regarding their arrester position and number of rows. Cylindrical cells feature multiple rows with arrester being on opposite sides [25, 26]. Prismatic cells feature either single-rowed [27, 28] or two-rowed modules [29, 30] while the arresters are regardless of the row always on the same side [28, 31]. Battery modules with pouch cells show single-rowed cells with the arresters being positioned either on the same or the opposite side [26, 31].

3.2. Cell contacting

The electrical connection of all individual cells is of essential importance [32]. The main function of electrical cell contacts is to transmit electrical energy with minimal losses. Hence, the electrical resistance of the cell contacts should be as low as possible. Additionally, the electrical resistance should remain constant over the entire service life of the Li-ion batteries. Otherwise an even aging of the battery cells, which depends largely on the operation of the cells, can no longer be guaranteed [33]. Hereby, all cell contacting systems dependant on the cell type (cf. Fig. 1). Cylindrical cells are adhesive bond connected with busbars by a welding technology and are optionally wire bonded [34, 35]. In this case no support plates are necessary. Prismatic cells are either adhesive bonded by welding (e.g. laser), with busbars (e.g. connections sheets) [32] and support plates or traction/form fit connected with screwing/latching as joining technology and hole-busbars as bridge [31, 29]. Pouch cells can also be connected by adhesive bond connections by welding (e.g. ultrasound) and in either tab-to-tab [32] or tab2busbar bridges [36] without support plates. Otherwise, it may be connected by a traction/ form fit connection with screwing as joining technology and screw thread-/ hole-busbars as bridge without any support plates [36].

3.3. Fixation of Li-ion cells

In this paper, the fixation is divided into a primary fixation, which keeps the individual cells at its foreseen place (cell-to-cell fixation) and a secondary fixation, which detachably or non-detachably fixates the cells to a group with e.g. side or end panels (cell-group fixation). When fixating the battery cells, one has to distinguish strongly between the individual cell types. For pouch cells, cell frames are often used as primary fixation, in which the cells are inserted, redundantly sealed and flexibly tensioned [37]. The spaces between the cells could even be additionally used for a cooling system. Optionally, pouch cells may even be glued [37]. Cylindrical cells have to be fixated by rigid spacers, spacer strips or mounting brackets (including recesses) [35, 11]. Due to the geometrical shape of the cells, gaps are created which can optionally be used for cooling systems (e.g. [11]). Additionally, gluing can be used as primary fixation of cylindrical cells [38]. Lastly, prismatic cells can be primarily fixed by gluing (optional) [30]. This requires a light, elastic joining medium to avoid air pockets and thus achieve complete contact and insulation. When using cell frames or gluing as primary fixation form, the secondary fixation will independently from the cell type either comprise of non-detachable joined side panels (e.g. welding) [38, 28] or detachable joined end plates or side panels (e.g. tension/ stretch units, threated bar, tension rod, tightening straps) [39].

3.4. Battery module housing

The module housing accommodates the cells of a battery module and therewith plays a decisive role in the functionality, safety and service life of the energy storage system [21]. It shields the sensitive components from harmful environmental influences such as water, moisture and dust, and is crucial for a long-term, safe and reliable operation [21]. The module housing may or may not be function-integrated in the cell fixation [40, 39] and consist of one, two or multiple parts [29, 28]. Ultimately, the joining type of the individual parts can be detachable joined [41] or non-detachable joined [28].

3.5. Thermal management

A fully functional battery can only be operated optimally within a narrow temperature range. During storage, temperatures up to +60°C and during operation, temperatures up to +40°C do not pose any problems and offer a first starting point for a thermal upper limit [42, 43]. At cell temperatures below 0°C the battery can even be damaged [44]. The Li-ion batteries should be actively cooled or heated to ensure the small operating temperature windows and to avoid temperature differences [42, 43]. The thermal management is not dependent upon a specific cell type. Nevertheless, a distinction of two main cooling types can be made [43]: Air cooling and fluid cooling. For the air cooling the battery cells are cooled directly with conditioned air. The required air can be tapped at different points in the vehicle, e.g. from a refrigerant-air evaporator [27]. Active cooling via fluid coolants represents a very flexible and efficient cooling method. The fluid coolant flows through the cooling plates and provides thermal regulation of the cells. Additionally, fluid cooling can also be differentiated into various variants regarding to their spatial arrangements. The spatial arrangement is mainly based on the necessity of thermal contact with the battery cell itself in order to cool every single cell. Herein, it can be separated into floor/head cooling, side cooling, arrestor cooling, cooling plates (fluid-led) and heat-conducted plates [42]. These fluid cooling systems are more complex due to the direct contact of the cooling apparatus with the cell compared to air cooling methods. Thus, the thermal management can be split into fluid and air cooling while the fluid cooling type can be further differentiated by its spatial arrangements.

3.6. Battery management system (BMS)

The BMS is an independent control unit that monitors and controls the complete battery system activities and therewith ensures safety and stability. This includes the calculation of the battery state of charge (SOC) and aging state (state of health, SOH) as well as the cell voltage, currents and temperatures to guarantee the safe operating window of each individual cell [45]. Regarding the component characteristics of the BMS and its periphery, it can be mainly differentiated within four topologies used by many companies nowadays. Hereby, it is essential to employ a three-tier concept consisting of cell monitoring units (CMU), module management units (MMU) and pack management units (PMU) when differentiating the BMS topologies as described in [46]. A centralized BMS unites all three monitoring units (PMU, MMU and CMU) in a single system that performs all tasks required by the BMS [46]. In the second topological possibility a central control unit (master) and slave units are connected to each other, whereas the slave units are further attached to each cell. The master unit integrates all PMU functions, while the slave units comprise the CMU functions. Although, the master unit comprises the PMU and MMU some of the functions of the MMU, e.g. inter-cell balancing, can be performed either by the master or the slave units, depending on the selected balancing concept [46]. The third topological possibility is based on the same master/slave system, where the master unit integrates the PMU functions and the slave integrates all MMU and CMU functions [46]. Lastly, the fourth topological possibility is a distributed software BMS, in which every subsystem manages one or more cells including functionalities from all three tiers (CMU, MMU and PMU). Therewith, a central control unit is distinguished, and the battery pack is equally and collaboratively managed by all subsystems [46].

To sum up, this chapter has allocated six key battery module components and systematically illustrated the state-of-the-art module manifestation variety. While some manifestations of module components show dependencies to the cell, e.g. cell contacting or cell fixation, others are rather independent, e.g. BMS or thermal management. Caused by the different product manifestations and the mentioned dependencies, an adoption of the disassembly sequence seems to be from high importance.

battery cell	A
cell contacting	B
thermal management	C
cell fixation/modul housing	D
BMS & periphery	E

	A	B	C	D	E
A	x	x			
B		x			
C					
D				x	
E					
mechanical joints					

	A	B	C	D	E
A	x		x	x	
B					
C					
D					
E					
chemical joints					

Fig. 3. Positions of mechanical and chemical non-detachable joints

4. Process-related challenges for disassembly

A major challenge when dismantling battery modules in cells are the non-detachable joints in modules in combination with the hazards posed by the Li-ion battery cells. In the following, non-detachable joints frequently used in battery modules are localized as well as the key hazards are identified.

4.1. Localisation of non-detachable joints

A basic distinction is made between mechanical (especially welded joints) and chemical joints (adhesive joints). The positions of the identified mechanical and chemical joints are shown in Fig. 3.

Mechanical non-detachable joining connections can be especially identified when contacting the cell (cell-cell, cell-contactor) and within cell fixation or housing. The choice of this type of joint is justified by the high requirements placed on the connection. For cell contacting, a particularly high mechanical strength (for both static and dynamic mechanical loads) as well as temperature resistance must be present [31]. Furthermore, the electrical contact resistance should be as low as possible [31]. Depending on the utilized cell type, laser spot welding (prismatic cell, pouch cell), ultrasonic welding (pouch cell), ultrasonic wedge bonding (cylindrical cell) and projection welding (cylindrical cell) are used for cell contacting [31]. The module housing, which can also include an integration of the cell fixing function (especially secondary fixing), as explained in more detail in the last chapter, can be joined by a welded joint [47]. Adhesives are used in battery modules as structural elements, for electrical insulation, sealing and for thermal management as a heat conducting compound [48]. Adhesive bonding is especially found between the individual cells (independent of cell type), between cells and cooling plates as well as cells and housing plates, as it is illustrated in [28]. Epoxy resin, polyurethanes or adhesive tapes [28] can be used as adhesives.

4.2. Li-ion battery hazards

Li-ion batteries are classified as hazardous goods and therefore require special treatment. According to [9], the hazards can be divided into 3 sub-categories: Electrical, Chemical and Fire/Explosion. Electrical hazards may be called electric shock and further associate burning. This is due to the high system voltage of 300 to 400 volts, especially at battery system level. Moreover, short circuits lead to heating of the battery. Among the chemical hazards, the carcinogenic nickel or cobalt can be mentioned, which are contained in the active material of the cathode. If the electrolyte escapes and comes into contact with water, the solution salt $LiPF_6$ can also produce caustic liquid acid HF. If a critical temperature is exceeded, an exothermic reaction can occur, which is widely known as thermal runaway. On the one hand, due to gas formation and thus pressure build-up, thermal runaway can lead to the escape of toxic gas or even explosion. On the other hand, the thermal runaway can degenerate into a fire due to highly flammable carbonates in the electrolyte such as ethyl methyl carbonate (EMC) and ethylene carbonate (EC). Triggers for heating and consequently a thermal runaway can be short circuits or overcharging [49, 9]. Causes for a short circuit during battery module disassembly, subsequent heating and thus thermal runaway may be mechanical deformation or piercing with a sharp object. Furthermore, an external short circuit between the two electrode poles through an electrically conductive body will lead to heating and may eventually result in a thermal runaway. Hence, it is recommended to permanently monitor the temperature of the cells at this point for the detection of critical conditions in order to eject the cells or even the entire module in an emergency scenario. A critical temperature rise gradient can be e.g. 0.2 °C/min [50]. The monitoring can be done with the help of a thermal imaging camera (contactless) similar to the disassembly of an iPhone 6 [13].

In summary, non-detachable joints can only be detached using destructive or partially destructive separation processes [16]. On the other hand, these separation processes pose a great risk when dismantling modules with dangerous Li-ion cells. For example, damage to the cell envelope can cause leakage of electrolyte and further a formation of hydrofluoric acid [9]. Another example is the thermal runaway, the worst-case scenario for Li-ion batteries, which can be caused by a short circuit or excessive heat input during disconnection. For the separation of the different kind of non-detachable joints it is essential to make a specific selection of cutting processes with a wide range of operations and a safe parameter space. At the same, the battery cell should be monitored regarding the temperature to detect critical situation.

5. Conclusion and Outlook

In this paper, the key challenges of dismantling Li-ion battery modules into cells were systematically identified and classified. On the one hand, the variety of battery modules and their components represent a product-related challenge. Capturing a vast diversity of variants was carried out with the help of a morphological box based on the six battery module components. Consequently, the product-related challenge requests the disassembly system to be adaptable regarding disassembly sequence planning. A process-related challenge in the dismantling of battery modules is posed by non-detachable joints in combination with the hazards of Li-ion batteries. Non-detachable connections can only be separated with the aid of destructive or partially destructive separation processes, which require a safe process parameter space. The non-detachable joints in a battery module were identified and then illustrated in the form of a component relation matrix for both mechanical and chemical joints. The requirements to the disassembly system derived from the process-challenges is especially affecting the process planning: The choice of separation processes with a wide range of operations and a safe parameter space is crucial while monitoring the battery cells state. Finally, the product- and process-related challenges both affirm the use of an agile disassembly system.

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