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Challenges and Solutions of Automated Disassembly and Condition-Based Remanufacturing of Lithium-Ion Battery Modules for a Circular Economy

Jens Schäfer*, Ramona Singer, Janna Hofmann, Jürgen Fleischer

wbk Institute of Production Science at Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany

Abstract

This paper proposes a systematic approach for both, a remanufacturable battery module and an automated remanufacturing station. In the beginning the joints in a battery module are investigated and categorized, followed by an evaluation of alternatives. Based on the evaluation, a novel battery module and an automated remanufacturing station are presented. As a result, it is possible to replace an individual battery cell while maintaining the integrity of the battery module, leading to a value added product that can be brought back to market.

Keywords: Disassembly, Manufacturing system, Lithium-Ion Battery Remanufacturing

1. Introduction and motivation

With increasing market share of lithium-ion battery based electric vehicles, the question about recycling and remanufacturing gains in importance against the backdrop of scarce raw materials and the necessity of a circular economy. However, a state of the art lithium-ion battery module has several features that make a replacement of single cells nearly impossible and the sheer number of electric vehicles makes fully automated disassembly inevitable. In electric vehicles, single battery cells are connected to each other to form a battery module. Several battery modules are then connected to form a complete traction battery together with additional component parts.

* Corresponding author. Tel.: +491523 950 2613; fax: +49 721 608 45005.
E-mail address: jens.schaefer@kit.edu

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Common joining technologies for the electrical connection of battery cells are laser welding, ultrasonic welding and resistance spot welding [1][2]. However, all of these joints are not detachable. On top of that, the solid case of a battery module often is inseparable as well. As a result, a defect of an individual cell leads to a dysfunction of the whole battery module and still working cells might therefore enter the waste stream, leading to higher waste flows [3].

Strategies for waste reduction and a circular economy for technical products include the 3R model (reduce, reuse, recycle), that has been extended by recover, redesign and remanufacture to a so-called 6R model [4]. Depending on the product performance compared to the original performance a further distinction can be made between remanufacturing, reconditioning and repairing [5]. Amongst these remanufacturing has the highest degree of work content, as it requires replacement of its components [6]. For design for remanufacturing (DfRem) both, the product and the process, have to be taken into account.

From the point of view of production science remanufacturing is an incomplete disassembly with a subsequent assembly. It is therefore necessary to take the manufacturing process into account and identify irreversible manufacturing steps. These irreversible steps either require a redesign of the product or a corresponding dismantling technology, if a redesign is not of equivalent performance.

2. Evaluation of alternative designs for a remanufacturable lithium-ion battery module

2.1. Methodology

The methodology applied in this paper is shown in Fig. 1. A state of the art battery module served as a starting point for developing a remanufacturable battery module. In general, production processes can be separated in reversible and irreversible processes. As an example bolts can be unscrewed whereas welds cannot be detached. After the classification of the production steps alternative designs with different manufacturing processes are analyzed. If these alternative designs are promising, preliminary investigations are carried out. However, alternative designs might lead to functional restrictions of the battery module, resulting in a lower performance. In this case dismantling methods have to be developed and qualified.

2.2. Analysis of production processes and joints in a state of the art prismatic hard case battery module

Within all production steps, that are needed in battery module manufacturing, joining technologies will be presented in detail, as they make up for most critical steps regarding remanufacturing, with reversible or detachable joints functioning as an enabler of DfRem [7]. In the following an overview of the production processes of prismatic hard case battery modules is given, as this type of battery module serves for the state of the art analysis.

The cells are stacked on a compressive plate with adhesive pads between them [8], shown in Fig. 2 (I). These pads combine different functionalities. During manufacturing they fix the stacked battery cells before they are mounted in the case. As the stacked prismatic cells are pressed later on, these pads also function as a flexible element in between. In addition, these pads can form a thermal barrier between the cells in the case of a thermal runaway. For these reasons it cannot be dispensed with the adhesive pad completely.

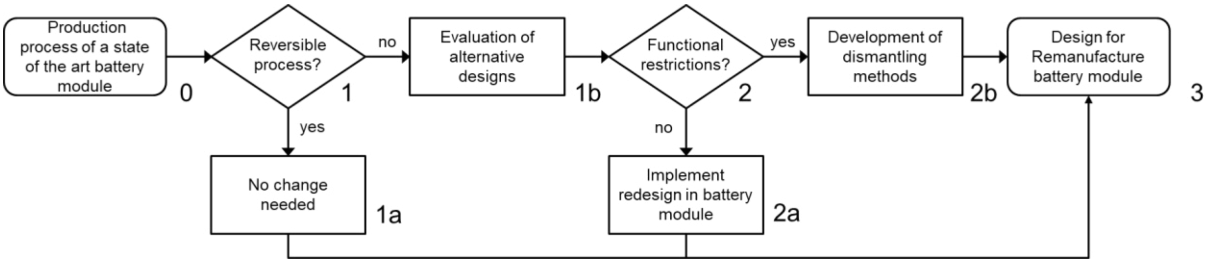

Fig. 1: Flowchart of the methodology applied to the state of the art battery module

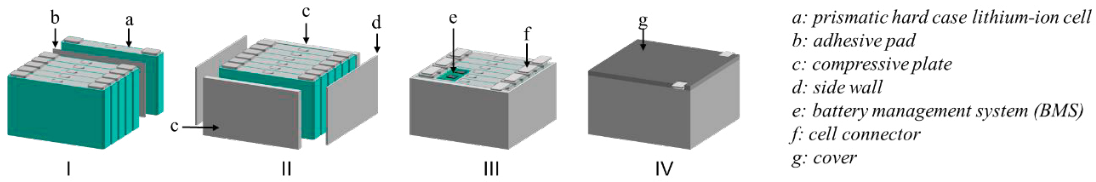

Fig. 2: Schematic representation of the production steps and parts for prismatic hard case lithium-ion battery modules

After the mechanical connection the cells are connected electrically through a cell connecting system made out of cell connectors and a battery management system, Fig. 2 (III). The cell connectors are laser welded onto the cell poles. Laser welds offer a low electrical resistance and a high mechanical strength. Common lasers include YAG fiber or disc lasers. The fiber-optic cable is then coupled to a scanner optic. Through beam oscillation the weld seam can be broadened. Furthermore different geometries can be welded and several cell connectors can be welded subsequently without the need of repositioning the handling unit. Laser welding and oscillation parameters as well as the weld geometry have an influence on electrical resistance [9][10] and weld spatter formation [11]. A cover can be clipped on to protect the battery module (Fig. 2, IV) and the production of the battery module is finished.

2.3. Evaluation of alternative designs and joining technologies

In the following, joints will be discussed in more detail, as they were identified as irreversible processes (Fig. 1, step 1): The joining of cells to each other (currently double-sided adhesive pads), the electrical connection (currently laser-welded) and the outer housing (currently laser-welded). Other joints investigated were the signal path between cells and the battery management system.

2.3.1. Electrical connection (cell connectors)

Concepts for twelve alternative joining technologies for the electrical connection were designed (Fig. 1, step 1b) of which three were investigated in more detail and are depicted in the following. Conductive glue was examined as an alternative to laser welds. Although this is not a dismantlable connection either, new design features could be integrated, including the possible use of active disassembly through chemical substances. The glue is mixed with conductive particles, mainly silver. However, it was found out that a high curing time was needed, making this process unsuitable for the desired application. Furthermore, a high particle load had to be selected in order to achieve a low contact resistance, making the glue uneconomic compared to the status quo.

Bond wires as an alternative to laser welded joints were investigated, as bond wires can be removed by pulling them off. As a prismatic cell is larger and thus contains more energy at the same voltage, the current flow is higher compared to cylindrical cells, where bond wires are often to be found. Due to the high current, the wire cross-section needs to be larger. However, the wire diameter of bond wires is limited. As a result many bond wires need to be welded onto the cell leading to a high cycle time.

In car body manufacturing many joints for single-sided mechanical fastening are realized by flow drill screws [12]. The main advantages are fairly low cycle times and a good automation capability. In comparison to press contacts, which have been compared to welded connections before [13], screws in general do not need any additional parts to maintain the contact pressure. As the flow drill screw forms a thread, it can be unscrewed if needed. Flow drill screws come in different sizes and threads. If the screw features a metric thread, it can be replaced by a regular screw off-the-shelf, making it ideal for remanufacturing. This promising alternative for the electrical connection was pursued further. Different flow drill screws were examined and tests were carried out. The tests included the measurement of the electrical resistance as well as temperature measurement. Minimal electrical resistance was achieved at a torque of 8 – 10 Nm, with laser welds still having a lower electrical resistance [14]. In conclusion all the alternatives above did not meet the set requirements for an electrical connection of the battery cells. For this reason the joining technology for the electrical connection was left unchanged. This made it necessary to qualify a dismantling technology for laser welded cell connectors.

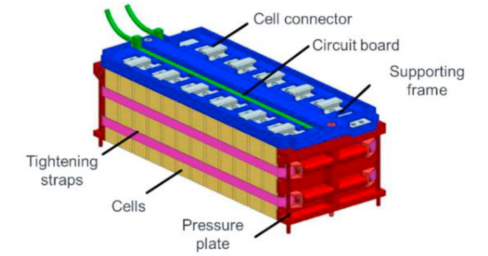

Fig. 3: Redesigned and remanufacturable battery module [8]

2.3.2. Mechanical connections (housing and adhesive pads)

As the current case of the battery module is laser-welded and therefore not detachable, the construction of the battery module had to be adapted. The side wall on each side was replaced by two tightening straps. However, the use of semi-rigid tightening straps might lead to extra effort and expense compared to the rigid side wall used before. The function of the double-sided adhesive film can also be achieved by single-sided adhesive film with reasonable adjustments in the production process. In contrast to the electrical connection investigated before, this redesign can be implemented in the battery module (Fig. 1, step 2a). The redesigned and remanufacturable battery module is shown in Fig. 3.

3. Development and construction of an automated remanufacturing station

An automated remanufacturing station is mandatory for the remanufacturing process. As a critical condition of the battery cells during remanufacturing cannot be completely excluded, this poses a potential threat for workers in the surrounding area. Furthermore, expecting an increasing number of electric vehicles, automated remanufacturing stations are turning more economic compared to manual disassembly. Additional advantages include a higher degree of standardization within the dismantling process and a higher quality [7]. The remanufacturing station that was constructed based on the remanufacturable battery module is depicted in Fig. 4. The system has a modular design and is built around a linear axis, which can reach all stations. Additional operations can be implemented later on, including the possible use of cameras for traceability or other sensors for condition monitoring. The key processes and components of the remanufacturing station are described in more detail in the following.

3.1. Removal of tightening straps

The compression of the battery module should be maintained during the whole remanufacturing process. As the tightening straps need to be removed to extract a cell, the compression has to be upheld by clamping cylinders, see Fig. 4b. As soon as the module is clamped by these cylinders, the tightening straps can be removed. The removal of the tightening strap itself is done by hand. All the cells are now accessible for the following processes and are transferred to the milling machine (Fig. 4c) via two linear axes (Fig. 4a).

3.2. Electrical connections

As mentioned before, no viable alternative to welded cell connectors was found. It was therefore necessary to develop an automated detachment process for these laser welded cell connectors (step 2b in Fig. 1). This detachment cannot be carried out without removal of material. One constraint is the one-sided accessibility of the connection. Furthermore, the cell must not be harmed in any way during disassembly. Possible damage includes penetration or destruction of the outer case, electrical shorts and deformation due to excessive pressure. Possible disassembly processes include milling or cutting.

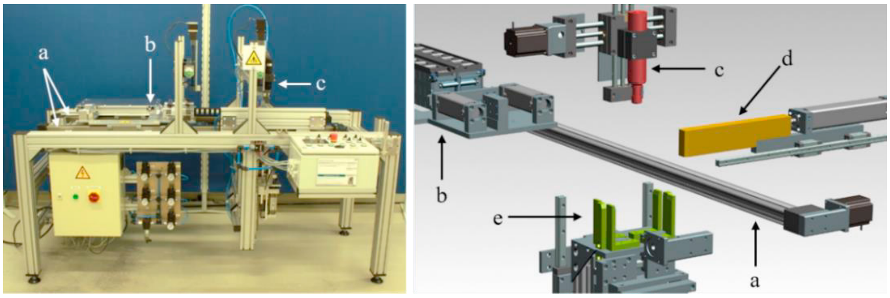

Fig. 4: Automated remanufacturing station (left) CAD model of the milling and cell replacement station (right) with a: linear axis b: module clamping c: milling machine d: placeholder e: gripper

When properly adjusted milling can meet these requirements. A drilling depth of 0.3 mm below the cell connector was found to be enough to remove the cell without any harm [8]. If the cell connector is not to be replaced as well the number of remanufactures is limited by the total welding area available. The positioning of the joints therefore has to be taken into account for a remanufacturable battery module [8]. The milling is done while the battery module is clamped. The milling machine is mounted onto an X-Y table and in combination with the linear axis three degrees of freedom can be achieved. All axes are driven electrically.

3.3. Cell removal and reassembly

In order to change an individual prismatic cell it has to be removed and a new cell has to be inserted. While removing and inserting the cell, the compression within in the battery module should be maintained. First the two neighboring cells are secured with the outer fingers of the gripper (Fig. 4e in green). The cell to be replaced is then clamped and pulled downwards, but not removed completely. After that a placeholder (Fig. 4d in orange) is inserted in the space between the neighboring cells. With the extended placeholder the cell can be removed completely. The cell then is taken out of the gripping station and a new cell is inserted. This new cell can then be lifted to the battery module with the placeholder still in. As soon as the cell is inserted the placeholder can be removed and the cell is lifted all the way up. This process can be repeated for all the defective cells in the battery module. The placeholder as well as the gripper are driven pneumatically and controlled via a PLC. With the new cell being in place, the module can be reassembled. The tightening straps are screwed back on the battery module and the clamping cylinders can be opened. In a last step the original cell connectors can be welded onto the new cells for which the original production facility could be reused. The complete work flow chart is shown in Fig. 5.

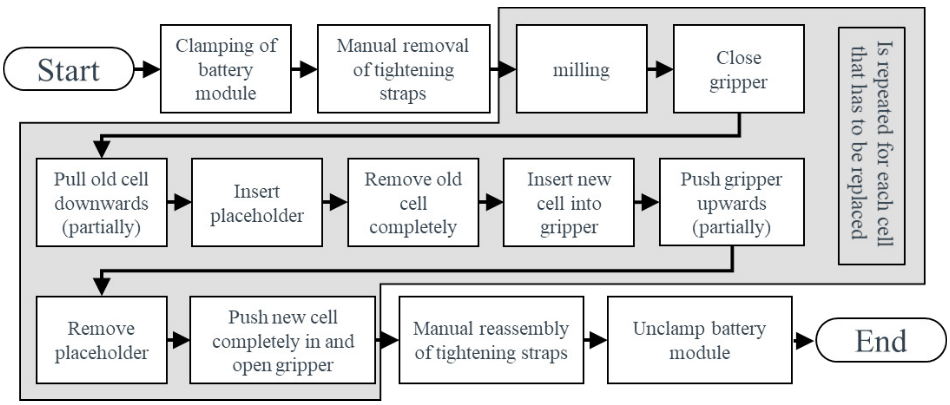

Fig. 5: work flow chart of automated remanufacturing

4. Summary

The analysis of a state of the art battery module has shown that the remanufacturing of it is not feasible as joints cannot be nondestructively dismantled. Therefore a systematic methodology for redesigning a technical product was proposed. This method was applied on a prismatic hard case battery module. Due to requirements on performance, not all of the joints within this module could be designed dismantlable. None of the investigated joining technologies proved to be of same performance as laser-welded cell connectors. This made it necessary to develop a dismantling technology. Based on the redesigned battery module an automated remanufacturing station was presented. With this remanufacturing station it was possible to replace individual cells in the battery module whilst maintaining the integrity.

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