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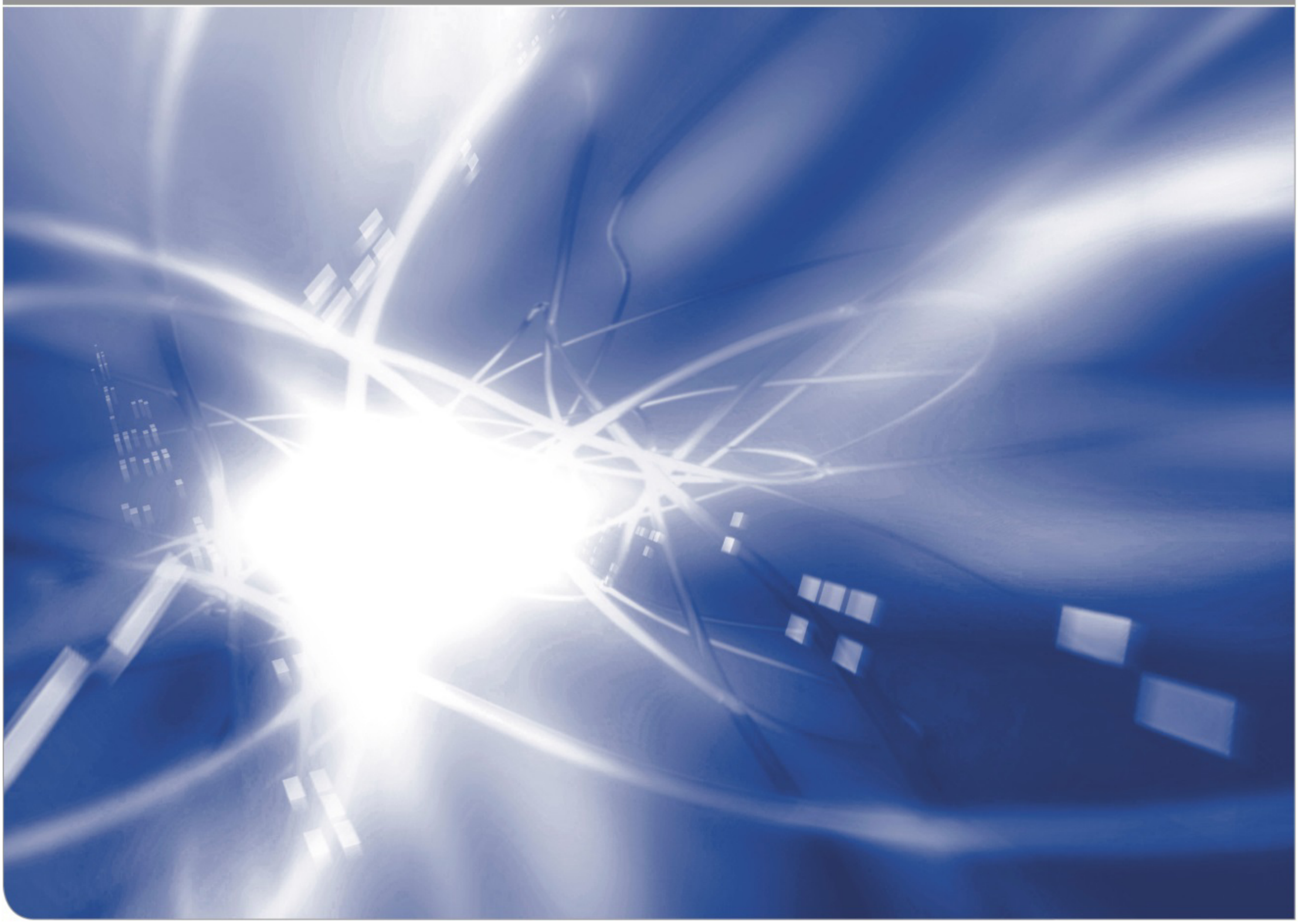
KIT SCIENTIFIC WORKING PAPERS 229



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[1] Institute of Product Engineering
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(2) Information on parallel publications in anthologies, conferences

(3) Details of projects, clients, sponsors, URLs, numbers and other project-related information is not entitled

facultative

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76131 Karlsruhe
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Impressum

Karlsruher Institut für Technologie (KIT)
www.kit.edu

2023

ISSN: 2194-1629

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Abstract

The usage of battery systems is an important factor for protecting the environment. However, currently the disassembly, reuse and recycling of the pack are still an issue. Battery cells are usually contacted by welding. This makes it nearly impossible to remove individual cells from the pack. As of now there is already existing knowledge of properties of detachable electrical contacts. However, no approaches exist that allow the use of detachable contacting, considering challenges in battery packs with multiple cells and their design. Disassembly of the pack is the main problem regarding a circular economy compliant design. Detachable cell contacts are one potential solution. The main challenge implementing this solution is to achieve a contact resistance as low and equally distributed as possible.

Therefore, the authors present a method that allows the initial design and optimization of a battery pack with a detachable contacting system. The design is based on initial requirements such as necessary contacting forces for individual cells and contact materials. In addition to technical functionality, sustainability and weight, cost-effectiveness will be considered for the evaluation of the individual designs. The best-evaluated concept is then designed and manufactured using rapid prototyping methods. Finally, tests will be conducted with the prototype and the associated actuating system to ensure functionality of the designed pack under different influences such as temperature or vibration.

1 Introduction

The reduction of greenhouse gas emissions is a central component of environ-mental protection. The transport sector accounting for 19 % of the total emissions is a sector with high focus on new technologies for reduction of greenhouse gas emissions [1]. A major trend in the transport sector is the move towards electro-mobility, which is not limited to privately used cars or commercial vehicles, but has also arrived in the field of micro mobility in urban regions [2]. In cities, there is an increasing supply of e-scooters and use of e-bikes, which offer themselves as a convenient alternative to public transport especially in urban regions.

An important component of electrically powered small vehicles is the battery, which is composed of several individual cells connected in parallel and series. The individual cells have slightly different characteristics and are all subject to aging, which can have a negative impact on the batteries' performance [3]. Due to this, the replacement of individual cells is shown as a possibility to increase the number of life cycles of a lithium-ion battery pack [4, 5].

The production of lithium-ion cells is a socio-ecological burden for the environment due to the use of rare earths such as lithium, nickel or cobalt [6]. In addition, the deposits of the materials used for the production of lithium-ion batteries are limited, which is why the recycling of used battery cells is becoming increasingly important [7]. First life cycle assessments of lithium-ion batteries confirm the necessity to recycle single cells to reduce negative socio-ecological environ-mental impacts and respond to resource scarcity [8].

The replacement and recycling of individual cells thus depends on the cell's ability to be disassembled within the cell pack, which is largely determined by the contacting. Currently commonly used methods are welding, soldering or, less frequently, mechanical connections. The aim is to achieve the most constant, low-loss current flow possible over the operating period, so that the ultrasonic welding process is the most widespread due to low contacting resistances and stable connections [9, 10]. For the flexible replacement of individual cells, ultra-sonic welding is an unsuitable contacting option due to the material bonding. This results in the need for an easily detachable contacting of the cells, which enables the exchange and recycling of single cells.

2 State of Research

Electrical contacts are used in a wide range of applications. The most common application is for plug connections. In addition to the detachability of the contact, the main important property is the contact resistance, which is largely responsible for electrical losses. To determine the properties of electrical contacts, it is necessary to examine the contact surfaces in detail. It is not the apparent contact area that is relevant, but rather the contact area created on the basis of the surface contour, which then serves as an electrical conductor. In principle, the relation-ship is that conductivity increases as the proportion of the surface actually in contact increases. Fig. 1 shows a representative illustration of two surfaces in contact and their respective proportions involved in force transmission and electrical conduction. These proportions can also be influenced, for example, by extraneous layers due to aging or elastic and plastic deformation of the surface structure.

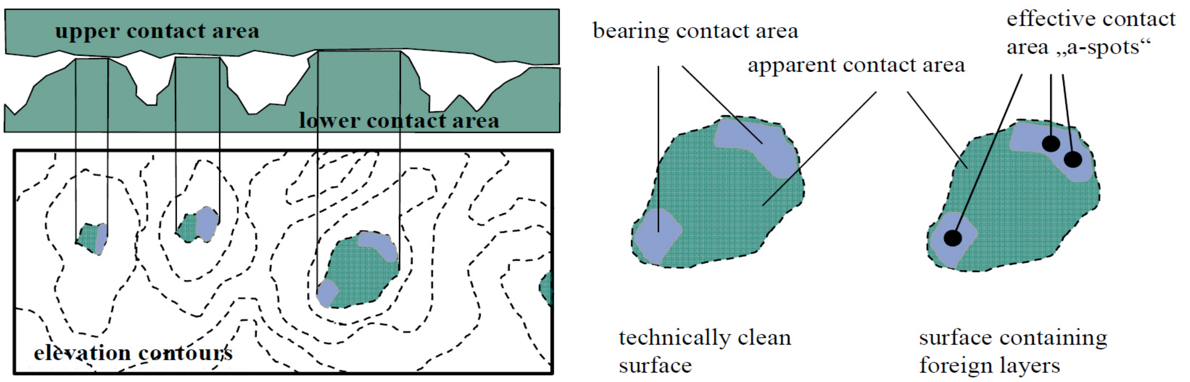

Fig. 1. Differentiation between apparent contact area, bearing contact area and actual con-ducting contact area [11].

For the electrical contacting of battery cells, welding processes are the most common method. In this process, the two cell terminals are welded with conductor plates in order to achieve electrical contacting and connection of several cells to form an entire battery pack. Typical processes for this are, for example, spot welding, ultrasonic welding or laser welding. The contact resistances resulting from the respective connection method can vary. Contact resistances resulting from spot welding and laser welding vary between 130 and 200 µΩ. The resistance values achieved by ultrasonic welding are in a significantly higher range for small contact areas. Electrical contacting by pure pressing, achieves comparable resistance values [12].

Investigations into the detachable contacting of 18650 battery cells have al-ready been carried out by Bolsinger et al. [13]. The focus was on influences such as contact force, material and aging of the contact surfaces on the contact resistance. Fig. 2 shows the results of a contact resistance measurement for these different influencing factors.

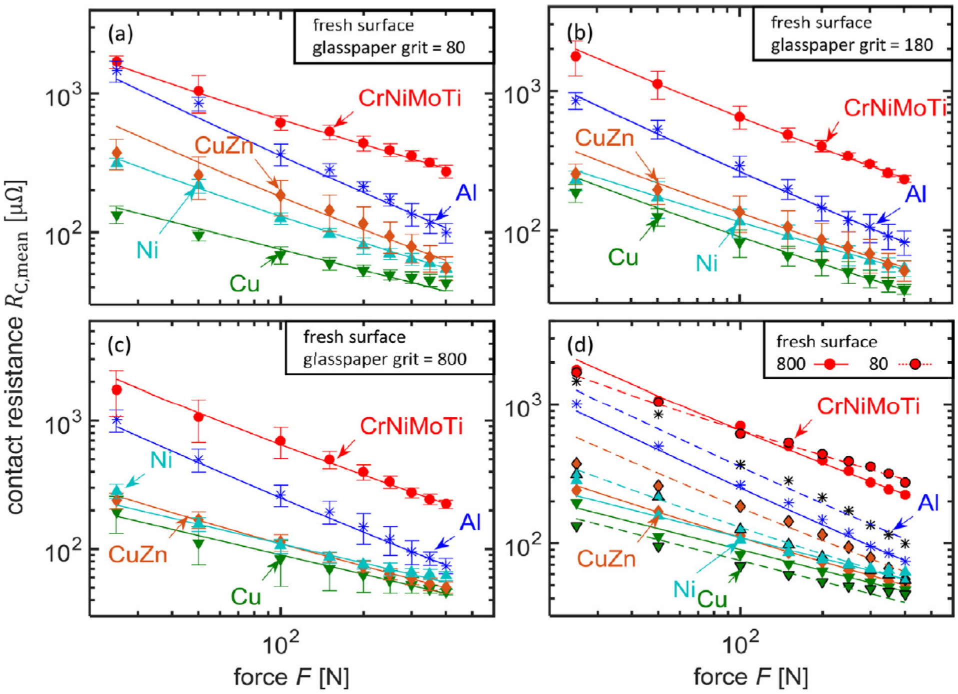

Fig. 2. Measured electrical contact resistances for different contact materials including standard deviation [13].

The main influence of the applied contact force across all contact pairs can be clearly seen. The contact resistance decreases with increasing contact force. The influence of the selected contact material is also clearly visible, with copper consistently providing the lowest contact resistance. The effect of aging of the con-tact surfaces and also of the surface roughness can be seen less clearly.

The implementation of a detachable cell contact for an entire battery pack has hardly been considered in the state of research to date, but only the consideration of individual cell contacts. In addition to understanding the cell contact, however, it is also important to investigate challenges and interactions when contacting several cells. Among other things, manufacturing tolerances or differences be-tween cell manufacturers can play a role. A clear gap in the current state of re-search is therefore seen in this area, the closing of which can make an important contribution to the cycle-compatible design of battery systems. Therefore, the objective of the present work is the conceptual design of a detachable cell contacting for cylindrical cells in an e-bike battery pack. Finally, the goal is to show the basic functionality of the designed battery pack and detachable cell contacting by manufacturing a demonstrator and conducting individual tests.

3 Methodology

In the following, the methodology for the concept definition of the battery pack with detachable contacting and its design optimization is described. The basic procedure of the methodology is shown in Fig. 3.

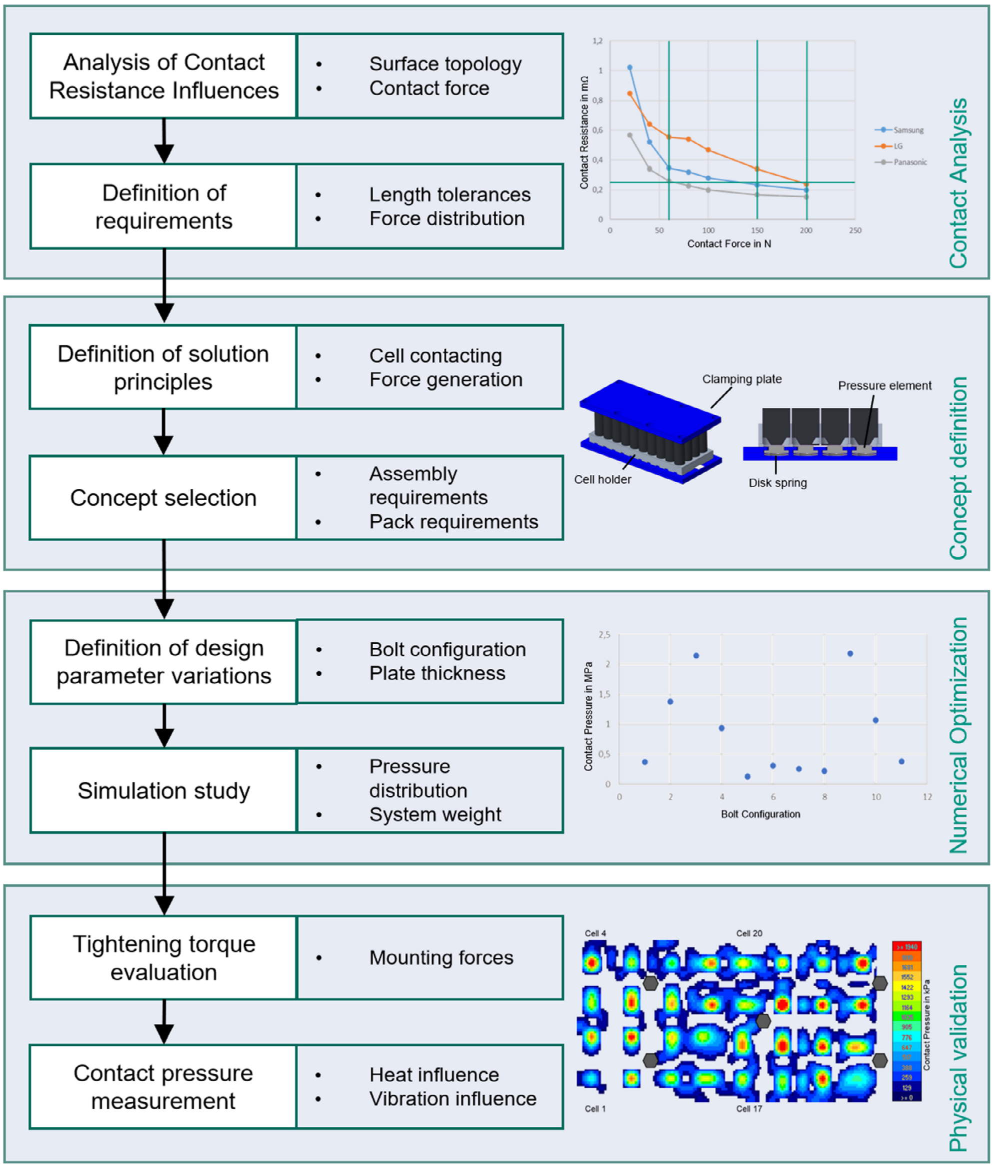

Fig. 3. Overall methodology for concept definition and design optimization.

Starting with an analysis of the contact properties between the cells and the con-tact material a necessary contact force is defined that assures a secure electrical contact with a suitable contact resistance. Important influences are for example the topology of the contact surfaces and the contact materials. A more detailed description of the conducted investigations can be found in previous work [14]. Based on these results initial requirements for the conceptional design of the battery pack with 40 cylindrical cells are defined. In a next step concepts for the detachable contacts of the cells as well as the overall pack design including the mounting parts are worked out. These are consisting of parts that are used for the realization of necessary clamping forces, equal force distribution, positioning of the cells, electrical contacting and compensation of production tolerances of the cells. Afterwards, a selection of the most promising concept is done based on basic criteria such as necessary assembly steps, the mass and volume of the system and complexity in the design. In this case the concept consists of two clamping plates, that will be positioned beneath and on top of the cells and can be tightened using multiple bolts. To compensate length differences of the cells disk springs are positioned beneath each cell.

To optimize the overall design of the battery pack under consideration of the defined requirements a simulative parameter study is conducted. For this purpose, a FE based model of the cell arrangement with disc springs and the clamping plates is set up that can be varied in multiple parameters. The investigated parameters are given in Table 1.

Table 1. Parameters for design optimization.

Parameter	**Investigated Values**
Bolt number	4, 5, 6, 8
Bolt position	10 mm increments at plate boundaries and spaces between cells
Clamping plate thickness	3 mm, 5 mm, 10 mm
Clamping plate material	PLA, Aluminum, Steel

The simulation results for all parameter combinations are then compared based on the pressure distribution on the individual cells as well as the systems weight and volume. For the most suitable combinations of bolt position, clamping plate material and thickness further topology optimizations are done to improve the shape of the clamping plates and therefore further reduce the system's weight.

Finally, the optimized design is used to manufacture a demonstrator of the bat-tery pack using rapid prototyping processes such as 3D printing and laser cutting. The demonstrator is then used to evaluate the functionality of the design regard-ing the detachable electrical contacting of the cells. For this purpose, measure-ments of the pressure distribution in the pack are done using a pressure mapping sensor. In a last step the gathered results are analyzed and used to define further improvements of the design.sein.

4 Results

In this chapter the results of the design optimization and physical tests on the demonstrator are shown. Main goal of the design optimization is to achieve an equal force distribution on the cells while keeping the weight and volume as well as cost of the battery pack as low as possible. Main influences on the force distribution are different cell lengths and bending of the clamping plates based on their thickness and bolt positioning. For all simulations the cell length was considered equal so that the influence of the described design parameters can be evaluated. In total a force of 4000 N is applied to the upper clamping plate. The evaluated minimal contact pressure over the whole pack for different 5 bolt con-figurations using aluminum clamping plates of 5 mm thickness are shown in Fig. 4.

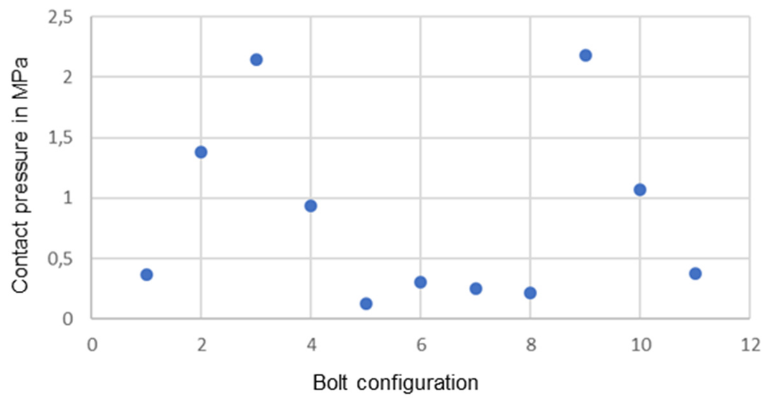

Fig. 4. Simulated minimal contact pressure on cells for different bolt configurations with 5 bolts.

It is visible that the choice of bolt positioning has a great influence on the lowest pressure on the cells. In this case configuration 3 and 9 are showing the best results, where configuration 9 is showing the bolt positions also seen in Fig. 5. Comparing the results of different number of bolts showed a significantly smaller influence where the best configuration using 4 bolts resulted in a minimum contact pressure of 1.9 MPa, 5 bolts in 2.2 MPa, 6 bolts in 2.25 MPa and 8 bolts in 2.2 MPa. Therefore, bolt configuration 9 from Fig. 4 is considered the best option. Comparing different materials and plate thicknesses showed the best result for either a 3 mm steel plate or a 5 mm aluminum plate. Other options were either resulting in bolt configurations showing no contact for some cells at all or equally good results for all bolt configurations which indicates an oversized stiffness of the clamping plates. In a further step the two described options with 5 bolts are used for a final topology optimization of the clamping plates.

After the simulation-based design optimization the demonstrator was manufactured. It consists of two steel plates with each 3 mm thickness, 40 dummy cells of type 18650 which are not containing any active material but have the same housing and terminals as regular cells, five M4 bolts that are positioned in between the cells and used to compress the two clamping plates. The configuration is shown in Fig. 5. Additionally, two disk springs are positioned under each dummy cell. They are connected in series allowing a maximum displacement of 1 mm. For positioning of the cells, a 3D printed PLA cell holder is used. For better application of the force to the cell terminals PLA cylinders with 6 mm diameter are positioned on both sides of the cells.

For the measurement of the pressure distribution a Tekscan pressure mapping sensor 3200E was used. It is positioned directly on top of one side of the cells. For an initial evaluation of the necessary tightening forces multiple tightening torques ranging from 0.2 Nm to 0.8 Nm were tested. The measured pressure distribution for a tightening torque of 0.8 Nm and 5 bolts is shown in Fig. 5.

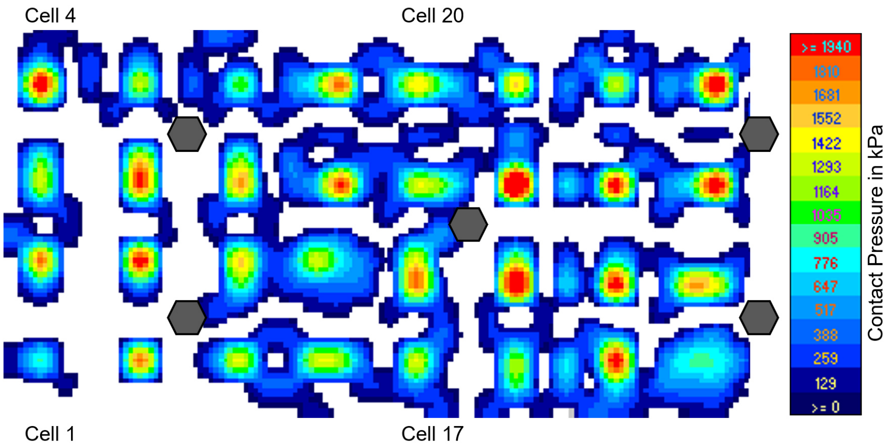

Fig. 5. Measured contact pressure on excerpt of the 40 cells for 0.8 Nm tightening torque.

It is clearly visible that a contact on each cell can be achieved despite the length tolerances of the dummy cells.

An investigation of thermal effects on the pressure distribution was done by comparing a measurement at 20 °C and 60 °C using a tightening torque of 0.6 Nm. Analyzing the parts after the measurements showed plastic deformation of the 3D printed PLA parts which also resulted in a visible pressure loss. Based on this observation all parts that are part of the force distribution should be made out of materials with higher thermal stability, especially when higher temperatures for long times are expected.

Since the investigated concept consists of multiple bolted connections that are responsible for the applied pressure and therefore electrical contact properties, further tests are done regarding the pressure distribution during vibration of the battery pack. For this purpose, the battery pack is mounted to a Tiravib shaker system and multiple frequencies and forces are applied in axial direction of the cells. Table 2 shows the applied vibration configurations.

Table 2. Parameters for vibration tests.

Parameter	**Investigated Values**
Frequency	20 Hz, 40 Hz, 60 Hz, 80 Hz, 100 Hz, 120 Hz, 140 Hz, 160 Hz, 180 Hz, 200 Hz
Force	50 N, 200 N, 400 N
Tightening Torque	0.8 Nm reapplied after each force step
Time	60 s for each frequency

The test sequence is done in 3 main steps with different applied forces after which the 5 bolts of the battery pack are retightened. For each force set ten different frequencies are applied for 60 s each summing up to a total time of 10 min. The measured overall applied force on the cells during the vibration test is given in Fig. 6.

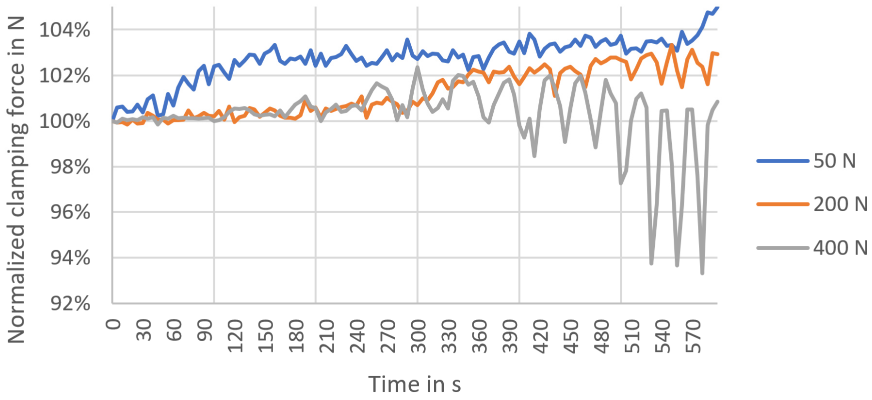

Fig. 6. Normalized force on battery cells during vibration test

Observation of the demonstrator after each vibration test showed no signs of untightened bolts for all of the investigated parameter sets. This can also be seen in the measurement of the applied clamping force where the force at the beginning of the tests is the same as the force at the end of each test. For a shaker force of 400 N signs of clamping force loss can be observed for higher frequencies starting at 140 Hz during the test which are also returning to initial values after removing the vibration. This effect was not visible for a shaker force of 50 N and only in a reduced form for 200 N.

5 Summary and Conclusion

In this work, the basic feasibility of detachable contacting of cylindrical battery cells for the application of an e-bike battery was investigated.

Based on a cell contacting concept that consists of two clamping plates and bolts to apply a force to the electrical contacts of the cells and also disc springs to ensure an equal force distribution between the individual cells, an initial de-sign of a battery pack with 40 cells was designed. For this design a FE based parameter optimization was conducted. It showed that the usage of 5 bolts in case of this 40-cell arrangement showed good results regarding the pressure distribution. Also, the usage of steel clamping plates with 3 mm thickness or aluminum plates with 5 mm thickness showed beneficial results. The simulation results also showed that a further increase of the number of bolts didn’t result in a better pressure distribution.

Using this optimized design, a demonstrator was manufactured that was used to conduct different tests to ensure technical feasibility of the contacting concept. Therefore, initial tests regarding necessary assembly forces were conducted. The pressure distribution results showed that in the case of 5 bolts the necessary tightening torque of 0.8 Nm can be manually applied. Investigations of thermal effects showed that a pressure loss can be seen when high temperatures are ap-plied over a long period of time due to plastic deformation of used polymer parts. Vibrations tests showed that for the investigated loads no signs of loosening bolts appeared. A pressure loss of 6 % was measured during the vibration test for higher loads which then returned to the initial pressure after the vibration load was removed.

Summing up, it was possible to show that the usage of a detachable contacting system for 18650 battery cells in a battery pack is possible and the basic requirements regarding a suitable contact resistance can be achieved with a simple pack design.

In further steps, the designed battery pack can be further improved by replacing the cylindrical pressure elements with materials more sustainable under higher temperatures such as high temperature polymers or aluminum to avoid plastic deformation and therefore pressure loss on the cells over the entire life cycle of the battery pack. To avoid changing contact resistances due to vibrations, further improvement can possibly be achieved by isolation of the cell assembly in the housing using foam materials. Regarding a faster assembly and disassembly especially in higher quantities a preassembly of the pressure elements and disc springs with one of the clamping plates is beneficial. This would allow a much faster replacement of the cells and also a switch to other disc springs with a different stiffness would be possible. This would allow a fast adjustment of the battery pack to for example a different cell type.

6 Acknowledgments

This paper presents excerpts of the results of the project „ IC2 – Lösbare Zellkontaktierung zur Erhöhung der Demontage- und Recyclingfreundlichkeit von Batteriepacks" as part of the Innovation Campus Future Mobility. The authors are grateful to the Ministry of Science, Research and the Arts Baden-Württemberg for funding this project.

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KIT Scientific Working Papers
ISSN 2194-1629
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