7 SUMMARY

The goal of this thesis was to create innovative lithium ion battery production methods that would enable for easy customisation, reduce overall costs and improve overall energy density.

In the beginning a comprehensive background study was conducted: this included the overall patent search as well as focusing on key players on the market. The patents were found from distinct classifications for battery pack manufacturing. In addition search terms such as weldlesss battery and lithium-ion battery pack were used. It turned out that work on simplifying the use and production of batteries goes back more than 100 years. In 1904 an American inventor Frank Jackosn patented technology for spark generating automobile batteries. His main innovation was a method to connect cells without using wires to save time on maintenance. The most recent invention was made by American Neal Saiki who in late 2013 had patented technology for high conductive battery contacts. The key players on the light electric vehicle battery market that were looked at had patented mainly patented control mechanisms and algorithms. This shows that most of them are using standard welding procedure.

A lot of work has been done to develop the battery technology. There have been improvements on the cost reduction as well as control algorithms. However it was clear that there is little innovation regarding modularity and custom solutions. Therefore a beyond state of the art concept must include the possibility to mass produce and customise battery technology.

The background research indicated that one third of the final energy storage costs come from labour. Firstly, the costs can be reduced by simplifying the process of assembly. Most modern battery packs are created by welding conductive strips on battery terminals to create series or parallel connections. When not producing in mass the welding process is labour intense and therefore costly. This is why it was clear that solutions without the use of welding had to be developed.

The first prototype for a 16 cell battery module was created from POM as it offers great strength and machinability. The CNC milled prototype consisted of two 4 mm thick pressure plates and a mid-plane that was positioned to guide the cells. The battery elements were positioned so that the polarities would create desired layout of serial or parallel connections.

Connecting plates were designed to connect the cells to each other. These plates were milled out of 1060 aluminium for maximal conductivity. The plates as well as battery elements were positioned into a custom milled footprint in the non-conductive endplates. Everything was tied together by 4 mm threaded rods and tightened with M4 locknuts. The vertical position of the mid-plane was regulated by additional nuts half way.

After the initial assembly a number of problems appeared; some of them were impossible to fix and therefore it was decided to design and build another prototype. In general the idea of using pressure for connecting the battery cells was effective but the initial implementation lacked quality and strength.

The pressure plates were too weak as they bent through and did not sufficiently pressure the battery elements. Too thin plates could not properly house the cells which complicated the alignment and thus assembly. Therefore it was time consuming to assemble the battery pack. More importantly, it was impossible to conduct contact measurements as the pressure plates were closed and there was no access to battery terminals.

For the second prototype the mid-plane was discarded as it had little effect. The thickness of the pressure plates was increased to 10 mm for higher strength and better cell housing. Threaded rods were substituted with M6 bolts and instead of 6 connection points 20 possible options were created. In the design process a lot of effort was made to allow for contact quality testing. A layout of holes was created to allow access to measurement points.

Overall the prototype was much stiffer and allowed quality tests to be conducted. A testing rig was created to test the voltage drop at each contact point. For this 7 A of current was drawn from the battery pack which makes 60% of maximum allowed continuous load. The measurements showed that losses at battery terminals are fractional; making up to 0.1% of the overall capacity. After analysing the test results and calculating average scenarios it was clear that imbalance caused by the contact points is smaller than the balancing capability of the battery management system.

The second prototype proved that the technology works as the contact quality exceeded expectations. It also showed that this kind of assembling method is sustainable as there is no misbalancing issues in-between the battery cells. On the other hand mass of the battery pack was high; the overall energy density without connector and outer casing was at 140 Wh/kg.

The second prototype proved the viability of the connection technology but did not contribute to other goals of the work. As the module was CNC milled out from a single plastic sheet it did not offer great modularity, nor was it inexpensive. To experiment with mass-customisation principle a third prototype was created.

Prototype C was designed to reach maximum customisability at lowest possible costs. The general idea was to create a single unit that wraps one battery element and is inter-connecting with others. The design of the single cell units was inspired by jigsaw puzzles. The prototypes were milled from the same 10mm POM. Each unit housed one end of a battery cell; therefore two units were needed per element. The units were inter-connecting to each other on a single plane in any direction. This offered any battery layout whether in series or parallel to be created.

As the modules were connected by moving them relatively to each other pressure plates were needed to assemble the battery unit. These endplates would allow for even distribution of force created by the connecting bolts. The plates had to be custom made for any unique battery layout. Single units could be made using injection moulding process that dramatically reduces the overall costs. At the same time the pressure and connection plates are plane and can be produced using low-cost technologies like water jet cutting.

Whereas the first prototype proved the idea, the second prototype approved the contact quality and third prototype brought it all together by minimising costs and maximising customisability.

In addition to the inner mechanics it was decided to create an easy-to manufacture battery casing that would offer environmental protection. After comparing different manufacturing methods it was decided to use thermoforming for its low costs and ease of implementation. Luckily there was a possibility to produce prototypes using a vacuum forming machine at one of the laboratories at the university. The casing was made from two separate parts: top and bottom. The forming moulds were designed by general vacuum forming principles: 8 degrees of taper and a minimum of 6 mm radii were used. The moulds were created out of medium density fibreboard using CNC milling machine.

To guarantee best end results three different materials were chosen for prototyping: 2 mm sheet of Polycarbonate branded as Markolon, 3 mm sheet of PETG known as Vivak and regular 2 mm ABS. All three were used to prototype the lower part of the casing. PETG and

ABS both had good formability whereas the first tests with PC were not successful as bubbles appeared inside the material. This phenomenon could be controlled by pre-heating the material. Overall it PETG offered the best combination of strength, formability and aesthetics and was therefore chosen as the final material for the casing.

The production of the top part was done using only Vivak sheet. During the first production the plastic was left too long on the mould. This allowed the sheet to shrink making it difficult to separate the plastic from the wooden mould. Although the outer surface quality of the top was spectacular the mould was damaged as parts of the MDF sticked to the PETG.

The casing was assembled using adhesive recommended by Henkel. Although the joining process was successful it did not create a through seal needed to protect from the environment. Therefore the adhesive agent must be substituted in the future.

As the overall concept was to develop innovative technologies for battery pack manufacturing it was necessary to include the environmental aspect. Therefore a life cycle assessment was conducted. First of all the logistics were analysed. It came out that all the raw materials as well as battery cells are produced east from Estonia whereas the accessories and plastics west.

First of all an LCA audit was conducted on the design which indicated that the worst environmental impact is generated by the battery elements. At the same time battery management system had the worst impact to mass relation. When comparing all three materials for the production of the casing it was clear that polycarbonate has much higher environmental impact than PETG or ABS. In addition the LCA pointed out that recycled plastics pollute three times less compared to primary material. Besides materials the production methods were also compared. For a unit of mass the thermoforming process was supreme to injection moulding. On the other hand injection moulding allows using design principles that help to reduce the amount of material used. Nevertheless it was clear that for low-volume production thermoforming is a supreme solution.

All in all, the main goal of this thesis was to develop innovative technology for light electric vehicle battery production. To do this overall costs needed to be addressed, modularity to be developed and energy density to be raised. It is clear that the main goals of the thesis were achieved by the three prototypes built. In addition the results were confirmed by the conducted tests.

On the other hand there is still plenty of development to do. Final design of the battery module needs to be decided; the overall weight needs to be cut to improve the energy density. Lifetime and vibration shock testing need to be conducted as well as the thermoforming moulds to be optimised and reproduced.

Although it depends on the area of use it can be said that the 16 cell battery module is ready to be tested on the market.

8 KOKKUVÕTE

Antud magistritöö eesmärgiks oli luua innovaatiline liitium ioon akude tootmismeetod, mis võimaldaks lihtsat mugandamist, alandaks lõpphinda ja suurendaks energiatihedust.

Esmalt teostati mahukas taustauuring, mille käigus viidi läbi patendiuuring ja selgitati välja antud valdkonnas tegutsevate ettevõtete tehnoloogiad. Patente vaadeldi klassifikaatorite järgi, peamiselt keskenduti akupakkide ehitust reguleerivatele alateemadele. Lisaks otsiti ka kindlaid sõnapaare nagu *weldless battery* ja *lithium-ion battery pack*. Uuringust selgus, et rohkem kui 100 aastat tagasi tegeleti juba akusüsteemide lihtsustamisega. 1904. aastal patenteeris ameerika leiutaja Frank Jackson autoakude koostamistehnoloogia, mille eripäraks oli vedruklemmide kasutamine akuelementide liitmiseks.

Lähiaja olulisim patent antud valdkonnas on ameeriklase Neal Saiki 2013 aasta lõpu *High Conducitve Battery Contacts*. Käesolevas töös kirjeldatakse integreeritud vedruga kontaktorit, mille abil on võimalik akuelemente ühendada.

Üldiselt võib öelda, et kuigi akude valdkonnas on väga palju erinevaid patente, siis otseselt modulaarsuse ja erilahendustega on neist seotud vähesed. Kuigi on olemas mõned üksikud ideed kuidas kulude kokkuhoiu eesmärgil loobuda keevitusprotsessist, siis mitte ükski neist ei võimalda modulaarseid lahendusi.

Seega peab tulevikku suunatud lahendus võimaldama erilahenduste masstootmist.

Esimese 16 elemendile mõeldud prototüübi loomiseks kasutati POM plastikut. Antud materjal on tuntud kõrge tugevuse ja väga hea töödeldavuse poolest. Prototüübi loomiseks kasutati arvjuhitavat freespinki. Prototüüp koosnes kahest surveplaadist ja nende vahel asuvast juhtplaadist, mille ülesandeks oli akuelementide suunamine. Elemendid olid surveplaatide vahele paigutatud nii, et nad moodustaksid soovitud ühendusskeemi.

Akuelementide ühendamiseks kasutati ühendusplaate. Tegemist oli alumiiniumlehest freesitud detailidega, mis asusid spetsiaalselt neile loodud õõnsustes surveplaadil. Süsteemi kooshoidmiseks kasutati 4 mm. keermelatti ja M4 lukustusmutreid. Keskmise juhtplaadi asukohta sai lisamutritega muuta.

Esmakordse koostamise ajal ilmnes hulk probleeme, millest mõningaid oli võimatu parandada. Seega otsustati luua uus prototüüp, mille loomisel püüti vältida varem tehtud vigu.

Kuigi üldine idee - ühendada akuelemente kasutades vaid survejõudu, oli edukas, võib esimese prototüübi loomise lugeda siiski ebaõnnestunuks.

Surveplaadid olid liialt õhukesed ja nõrgad. Seepärast ei suutnud nad akuelementidele piisavalt survet avaldada. Samuti oli võimatu elementide korrektne positsioneerimine surveplaadile loodud jäljes. Kokkuvõttes oli mooduli koostamine väga tülikas ja aeganõudev. Kõigele lisaks puudus võimalus testida elementide ja ühendusplaadi vahelise kontakti kvaliteeti.

Teise prototüübi loomisel viidi läbi järgmised muudatused: loobuti vahepealsest juhtplaadist, suurendati surveplaatide paksust 10 mm–le ja asendati keermelatid M6 poltidega. Kui esimesel lahendusel oli võimalik surveplaate omavahel ühendada kuue keermelatiga, siis uuel prototüübil on poltidega ühendamiseks 20 ava. Selleks, et oleks võimalik mõõta elementide kontakti pinnal tekkivat pingelangu, loodi surveplaati avade süsteem.

Kuna uus prototüüp oli oluliselt jäigem, võimaldas see teha korduvkatseid. Pingelangu mõõtmiseks loodi katseseade, mis koosnes 1 oomisest takistitest ja lülitusmehhanismist. Pingelagu tekitamiseks matkiti tavakäitluses tekkivat olukorda. Akusid koormati 7 A vooluga mis moodustab 50% maksimaalselt lubatud pidevast tarbimisvoolust. Mõõtmised kinnitasid, et kontaktides tekkiva pingelangu tõttu kaob ääretult väike osa energiast – umbes 0,1 % paki mahtuvusest. Testitulemuste analüüs näitas, et pingelang põhjustab elementide vahel pingete erinevusi kuid need jäävad lubatu piiridesse.

Teine prototüüp tõestas, et keevitamisvaba tehnoloogia töötab – pingelangu ja seega energiakao väärtused olid väiksemad kui prognoositud. Samuti näitas andmete analüüs, et antud tehnoloogia on jätkusuutlik kuna ei tekita pikemas perspektiivis elementide vahel mahtuvuse erinevusi. Kuigi prototüüp B osutus väga edukaks, häiris mooduli suur mass. Üldine energiatihedus ilma pistiku ja juhtmeteta oli 140 Wh/kg.

Kahe esimese prototüübiga tõestati, et keevitusvaba tehnoloogia on väga potentsiaalne. Samas ei olnud tegemist odava ega liidestamist pakkuva lahendusega. Selleks, et eksperimenteerida erilahendusi võimaldavate ideedega, loodi kolmas prototüüp C.

C eesmärk oli luua võimalus toota erilahendusel energiasalvestussüsteeme võimalikult madala hinnaga. Põhiideeks oli luua üksik klots, mis seoks endaga ühe akuelemendi. Ühele akuelemendile kinnituks kaks klotsi, üks mõlemasse otsa. Antud lahendus võimaldas luua ükskõik millise ühendusskeemiga akusid kuna klotse sai omavahel tasapinnal igas suunas ühendada.

Klotside loomisel ammutati inspiratsiooni pusledest. Klotsid ühendusid omavahel samamoodi kui pusletükid. Selleks, et akuelementidele survet avaldada, tuli klotsidest ühele poole lisada ühendus- ja teisele poole surveplaat. Mõlemad on tasapinnalised detailid ja seega on võimalk neid odavalt toota. Klotse tuleks toota plastiku survevalu meetodil, mis suures koguses pakub konkurentsitult parima hinna. Plaate saab nii alumiiniumist kui ka plastikust toota vesilõikuse abil.

Esimese prototüübiga tõestati idee, teisega kontaktide kvaliteet ja kolmandaga toodi juurde ka odavate erilahenduste mõõde.

Lisaks sisemisele konstruktsioonile otsustati töö käigus valmistada ka akumooduli korpus. Eesmärkideks seati võimalikult hea kaitse väliskeskkonna eest ja odav ning lihtne tootmismetoodika. Kuna tegemist on tehnoloogiaga erilahendustele, tuli vaadelda meetoodeid, kus on võimalik toota ilma suure alginvesteeringuta ka väikeseid seeriaid. Antud tingimustele vastas kõige paremini vaakumvormimine. Õnneks sai prototüüpide tootmisel kasutada Tallinna Tehnikaülikooli vaakumvormimisseadet. Korpus koosnes kahest osast: kaas ja alus. Vormide projekteerimisel lähtuti üldistest vaakumvormidele määratud nõuetest. Vormid freesiti CNC pingil kasutades materjalina MDF.

Parima tulemuse saavutamiseks valiti prototüüpimiseks kolm sarnaste parameetritega plastikut: 2 mm polükarbonaat lehtmaterjal, 3 mm PETG ja 2 mm ABS. Parima võrdluse eesmärgil kasutati kõiki kolme erinevat materjali korpuse aluse valmistamisel. ABS ja PETG materjalid võtsid väga hästi vormi kuju samas kui PC vormimine oli oluliselt keerulisem. Lisaks sellele, et PC ei tahtnud väga vormi kuju võtta tekkis kuumutamise käigus materjalisse hulk läbipaistvaid mulle. On teada, et selle vastu aitab materjali eelkuumutus, mis juhib niiskuse materjalist välja. Kokkuvõttes pakkus parima kompromissi tugevuse, vormimise ja visuaalse poole pealt PETG materjal, mida otsustati kasutada lõpliku korpuse loomisel.

Vormi kaane tegemiseks kasutati samuti vaid PETG materjali. Esimesel katsel ei olnud võimalik plastiklehte koheselt vormilt eemalda. Seetõttu jõudis materjal kahaneda ja tugevalt vormist külge jääda. Plastiku eemaldamisel vigastati kahjuks ka vormi, mis muutis edasised materjalikatsetused võimatuks.

Korpuse koostamisel kasutati Henkeli poolt soovitatud liimi 3090. Tegemist oli kiire kuivamisega värvitu ainega, mis suudab täita ka väiksemaid tühimikke. Vormi koostamine õnnestus kuid kuna antud liimaine tihedus on väike, siis ei õnnestunud täielikult mooduli tihendamine. Tulevikus tuleb katsetada teisi, suurema viskoossusega tooteid.

Kuna töö eesmärgiks oli luua tulevikku suunatud tehnoloogia ernegiasalvestuslahendustele, tuli läbi mõelda kõik toodet mõjutavad aspektid. Keskkonnamõjude hindamiseks viidi läbi toote elutsükli analüüs (LCA). Esmalt vaadeldi kogu tootmisprotsessiga seotud tarneahela logistikat. Selgus, et kõik toormaterjalid imporditakse Eestist vaadatuna idast ja komponendid läänest.

Emalt viidi läbi LCA audit, mille tulemusena selgus, et suurim keskkonnamõju on akuelementidel ja kõige suurem mõju massiühiku kohta on elektroonikal. Võrreldes korpuse materjalideks testitud kolme plastikut, selgus, et PC mõju loodusele on oluliselt raskem kui PETGl või ABSil. Analüüsi käigus selgus, et taaskasutatud plastiku keskkonnamõju on ligi kolm korda väiksem kui uuel. Lisaks toormaterjalidele võrreldi ka tootmismeetodeid. Suurtes kogustes on mõistlik kasutada survevalu tehnikat kuna seeläbi on võimalik vähendada materjali kulu. Väiksemate koguste puhul on ainuõige kasutada vaakumvormimist.

Antud magistritöö eesmärgiks oli arendada uuenduslikke meetodeid kergelektrisõidukite akude tootmiseks. Selleks tuli alandada omahinda, arendada liidestamisvõimalusi ja tõsta energiatihedust. Võib kindlalt väita, et peamised ülesanded said täidetud. Selle tõestuseks loodi 3 prototüüpi, mille abil testiti erinevaid olukordi.

Teisalt on veel palju teha. Tuleb valida akumooduli lõplik disain alandades akumooduli massi. Kindlasti tuleb läbi viia eluea- ja vibratsioonitestid veendumaks toote vastupidavuses. Samuti tuleb parendada vaakumvormimise vorme.

Kokkuvõtteks võib öelda, et 16- elemendiline akumoodul on valmis sisenema turule.