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A new packaging solution for Li-ion battery cells

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Abstract

The development of highly efficient batteries is a critical need in the automotive industry in order to enable the future success of Electric Vehicles (EV). The optimization of battery stacks integration in EV can greatly benefit from an improvement of Li-ion cells modular assembly and electrical interconnection, while ensuring a high level of safety. This is part of the technical challenges of the European SPICY project.
In this paper, we present a new polymer-based packaging concept for Li-ion cells. A modular approach is investigated in order to enable a high flexibility in the selection of power output and stack geometry. The design of the polymer packaging is described in details. In addition to the Li-ion cells and USB power bank packaging, a specific connector for packaging assembly is developed. The manufacturing of the initial prototypes by 3D-printing and demonstrators by injection moulding is described.

Keywords: polymer packaging, modular packaging, Li-ion cells, free-form battery, connectors, injection moulding, overmoulding, 3D-MID, electric vehicles.

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1. Introduction

Electric Vehicles (EV) are on the verge of becoming common place on roads throughout Europe (EUROBAT (2015)). Batteries can fulfil the need for a constant, efficient, clean, safe and renewable power supply for vehicles. Battery storage systems have been recognized by all stakeholders as a key enabling technology to optimise the energy recuperation and the energy management of the whole vehicle with an appropriate safety level while respecting the environment.

Automotive application involves the use of multiple Li-ion cells, connected one to each other to form a battery stack. In the most basic and common case, the interconnection of the Li-ion cells is achieved via metal bars and screws, or large diameter cables, resulting in heavy modules. Li-ion cell packaging can be gathered in 2 families: i) soft packaging (aluminium pouch film) or ii) hard packaging, generally in aluminium with 100s micrometres thickness. They have advantages in terms of weight or mechanical resistance/durability. However soft packaging can easily open during undesired events and hard packaging is not isolated surface. In any case, the connectors are not isolated. The new modular polymer packaging solution developed in the H2020 SPICY[†] project aims at reducing the overall device weight (intermediate weight between soft and hard packaging), while improving the required level of performances (Zhang et al. (2017)) and safety.

In this paper, we present a new packaging solution for Li-ion battery cells, based on polymer technologies and connector integrated, developed for a demonstrator containing 500 mAh Li-ion cells with $LiFePO_4$ graphite technology. First, the main requirements for the packaging are thoroughly described. Then the new polymer-based packaging solution concept is presented, and the design of both packaging and connector is detailed. Finally, the manufacturing of packaging prototypes by 3D-printing and demonstrators by injection moulding is described.

2. Concept

2.1. Requirements for Li-ion battery packaging developed

In order to meet the automotive standards, the new packaging solution must meet several requirements, with the adequate level of performances and reliability.

The first requirement for the packaging is of course to be chemically compliant with the components of the Li-ion cell (especially the electrolyte) and to ensure efficient water and airtightness. As this is already achieved by the soft Al pouch film (Figure 1), this requirement does not apply to the polymer packaging, enabling higher flexibility in the polymer material selection and on the packaging design.

Secondly, the packaging should protect the component from hazards as impact collision. In particular, it must efficiently protect the Li-ion cell in order to meet the UL1642 standard and limit as much as possible temperature increasing. In the SPICY project, different cell packaging with the same electrodes, separator and electrolyte, having all 17Ah of capacity, have been evaluated in abusive conditions according to UL1642 standard. In particular, nail penetration tests were performed (Figure 2.a). Piercing the battery simulates an internal short-circuit. Cells were pierced fully charged at 25°C via the introduction of a conducting element across the casing. Prismatic hard packaging cell (600µm aluminium thick) and prismatic soft packaging cell (40µm aluminium thick with polymer film on both sides) were compared. During the tests, smokes were observed for the rigid architecture but no spark, no flame, no explosion were observed, which is compliant with the UL1642 for both cells. However, the maximum temperatures recorded were 110°C for the hard packaging cell and 32°C for the soft packaging cell (Figure 2.b). In this test evaluation, cells could deform but only a slight deformation occurred for the soft packaging cell. We explain the result by the fact that the hard packaging cells are directly connected to one terminal and the

Fig. 1 500mAh battery cells with soft Al package

[†] http://www.spicy-project.eu/

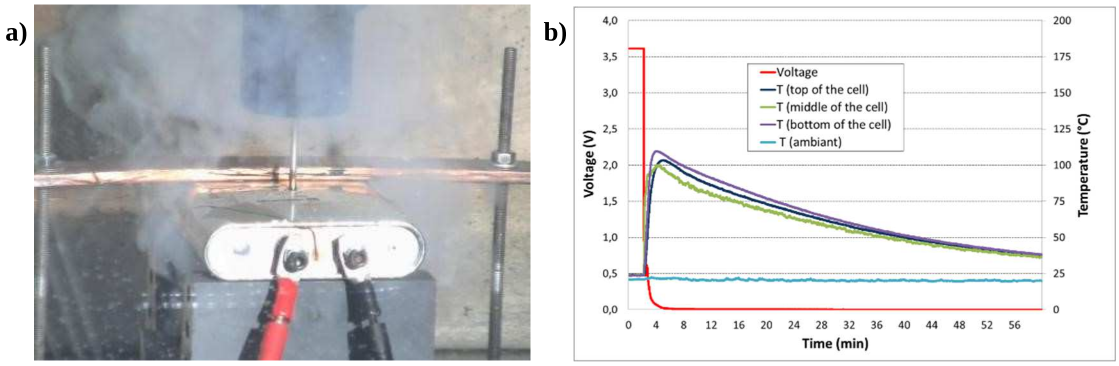

Fig. 2 Prismatic hard packaging cell during nail penetration test (a), temperature measurement for hard packaging cells of 17Ah (b)

short circuit induced by the nail get a lower resistance compared with the soft packaging, which is isolated. And so having a packaging isolated should be safer.

Cells were also evaluated by a thermal runaway test in a pseudo-adiabatic calorimeter, following the "Heat-Wait-Seek" protocol: from an ambient temperature, the temperature is raised for a given temperature step, then stabilized until an exothermal reaction of the cell is detected. If not, a new temperature step is done. An exothermal reaction is considered when self-heating is higher than the temperature rate sensitivity measured. For both cells, thermal runaway temperature of 95°C was observed. However, for the hard packaging cell, opening of the venting occurred at 130°C whereas flying parts of the active mass were observed for the soft packaging. Soft packaging can easily open and hard packaging cells appear to be safer. The new packaging solution present the advantages to be rigid and isolated. However, the packaging should stay relatively light to not be a burden for the module. Here we have considered a hard packaging of 600µm thick for the aluminium of a hard packaging cell having a capacity of 17Ah. The new packaging is developed for a 500 mAh cell but in the aim to be integrated with 17Ah cell at the end. For a 500 mAh cell, a casing weight for the soft and the hard packaging cells with a design of 5.5x34x38 mm^3 are respectively of 0.7 and 7.5 g.

The third requirement is related to the electrical functionality: the polymer packaging design must allow the electrical interconnection of several battery cells with optimal electrical performances, while ensuring a total safety for the operator. A low resistance between every subsequent cells for parallel connection is required, with a target maximum value of 5 mΩ in this demonstrator. This specification is taken into account in the design and material selection for both the packaging and the connector. The operator electrical safety is requested at several stages: during the assembly of the Li-ion cell inside the packaging, during the handling of the closed packaging, and during the assembly of modules using the connectors. In addition, several poka-yoke ("mistake-proofing" features) are required in order to avoid any mistake in the mounting of the Li-ion cells, ensuring both an optimal operation of the battery stack and the total safety of the operator.

The last requirement is related to thermal properties as Li-ion cell durability is linked to the temperature management to a window not higher than 55°C. This point has not been addressed in this first packaging concept but cell temperature is monitored, and potential use of thermally conductive polymers has been considered for future versions of the packaging.

2.2. Selection of the polymer processing technology

One of the key features of the polymer packaging is to enable the electrical interconnection of the battery cells. Nowadays, 3D-MID (Molded Interconnect Devices) technologies enable the selective metallization of plastic parts, allowing the integration of electric and electronic features directly on the surface of polymer parts (Rastikian et al. (2015)). These technologies are already used in various applications, including antennas for mobile phones, sensors for automotive or medical applications, etc. By creating conductive traces directly on the polymer parts surface, these technologies usually result in a substantial device weight reduction, as the integration of PCB (Printed Circuit Board) is not required anymore to achieve the electric and electronic functionalities. However, usual 3D-MID technologies, in particular the Laser Direct Structuring (LDS-LPKF®) and the 2-shot moulding technologies, are not suitable for high current applications as the deposited copper thickness is around 10 µm. Although electrodeposition of copper enables the creation of thicker conductive layers, this solution is usually not economically viable. Thus, as battery packaging requires high level of current flow, standard 3D-MID technologies are not compatible with the targeted application. The selected solution for the development of the new polymer packaging concept is the overmoulding of metal inserts. With this solution, the dimensions of the metal inserts can be optimized to fulfil the electrical performances specifications, while limiting the cost for function integration.

2.3. Selection of polymer material

As mentioned above, the mechanical specifications for the packaging have direct consequences on the polymer material selection. In order to improve as much as possible safety of the Li-ion cells, polymer materials with high impact resistance are identified: polycarbonate (PC), acrylonitrile butadiene styrene (ABS) and ABS/PC. Compared to PC alone, ABS/PC blends usefully combines the toughness of PC with the high impact resistance of ABS. In addition, ABS/ PC is usually cheaper than PC alone.
The selection of the optimal polymer grade must also take into account other criteria, e.g the required level of viscosity. Two opposite behaviour are taken into account: a high viscosity provides a higher toughness, whereas a low viscosity greatly facilitates the injection moulding process. With a melt flow rate (MFI) of 18 cm^3/10 min (ISO 1133), Bayblend T65 XF ABS/PC material is a good compromise and is selected.

3. Packaging design

Usual battery stacks involve a defined number of Li-ion cells and cannot be easily modified. In order to increase the flexibility in the use of battery modules, the new packaging concept is based on a modular approach: individually packaged Li-ion cells can be assembled dynamically (Plug-and-Play approach) in order to reach the desired output power level. Thanks to this packaging concept, dedicated packages for a given power output is not required. This concept requires the development of both the Li-ion cell individual packaging and the connector between each package, as depicted on Figure 3.
The overall modular packaging concept has been patented by CEA (Berthe de Pommery, et al. (2015)), and is similar to a watch wristband: in addition to enabling the parallel interconnection of several battery cells, the design also enables the free rotation between 2 packages (± 180°). This offers a higher freedom in the assembly geometry, enabling various forms for the final battery stack. The round-shaped clipping interconnection between packaging and connector enables this rotation, while ensuring a proper electrical continuity.
In order to optimize the final cost of the device, the design of the battery cells packaging involves 2 half-packages with similar geometry: the same plastic part is used as bottom and cover of the Li-ion cell. This approach is highly cost-efficient as it requires the development of a single mould, instead of 2 different moulds.

3.1. Weight optimization

The optimization of the power to weight ratio can greatly benefit from a reduction of the packaging weight, while keeping the required mechanical performances. The selection of polymer instead of usual metal for the packaging is a first step in the weight reduction of the final modules. Not only polymers are usually lighter than metal, polymer processing technologies enable a higher freedom in parts design: complex geometries and fine features can be created by injection moulding. The optimisation of the packaging design enabled by polymer processing technologies leads to a gain in volume and weight for the device.

Fig. 3 Modular battery stack concept: Li-ion cells packaging and connectors

In order to improve the weight reduction, polymer material is also removed as much as possible where its presence is not mandatory. Thus, in the inner side of the packaging, a honeycomb-like structure is applied on half of the package thickness. This results in a reduction of the polymer material by 16%, while maintaining the mechanical properties at the targeted level. The finally results in an estimated Li-ion cells packaging weight of 18.3 g. This value is higher than the existing rigid Al packaging weight, but the new packaging integrates more functionalities, e.g. the protection of the Battery Management System (BMS) in the packaging.

3.2. Integration of poka-yoke in the packaging design

In order to avoid any inadvertent error during the mounting of the Li-ion cells in the packaging and the interconnection of the modules, several poka-yoke are implemented in the packaging design. These mechanical features prevent the operator to do mistakes during the assembly, especially regarding the polarity of the batteries. Three mechanical features are integrated in the final packaging design.

The first poka-yoke is the size of the round-shaped clipping structures for the interconnection between packaging and connector. Two different widths of clipping structures are implemented, corresponding to the two terminals of the battery (plus and minus). This difference prevents the assembly of the connector in the wrong way, thus ensuring the interconnection of the positive terminals of a battery with the positive terminal of a second battery (parallel assembly). The implementation of this poka-yoke influences the design of both packaging and connector.

The second poka-yoke is the clipping structures for the closing of each packaging. These structures are located on the edges of the packaging, and enable the closing of the device. With the same part being used as bottom and cover, the modification of the features size allows only one orientation for the closing of the device. This ensures that the two different round-shaped clipping structures are aligned.

The third poka-yoke is a groove inside the packaging, which allows only one position for the mounting of the BMS in the device. This ensures that the terminals of the Li-ion cells are always connected to the same round-shaped clipping structures.

3.3. Mechanical simulation of round-shaped clipping structures

The interconnection between a packaging and a connector is performed via the insertion of the metal cylinder of the connector in the round-shaped clipping structures of the packaging. The effort required for this insertion must be low enough to enable an easy manual assembly, while ensuring a sufficient mechanical strength to avoid accidental disconnection. The maximum recommended effort for the clipping is set to 50N, which is a standard value for assembly effort specifications in the industry.

A mechanical simulation of the clipping structure is performed using ANSYS software. The initial CAD design of the packaging is meshed (see Figure 4.a) and the adequate properties are applied to the materials, as summarized in Table 1.

Table 1. Mechanical properties of packaging materials.

Material	Reference	Young’s modulus (Pa)	Poisson ratio
Polymer	ABS/PC	$2.2\ 10^{9}$	0.4
Metal insert	Copper	$1.24\ 10^{11}$	0.3

The initial opening of the round-shaped clipping structures is 1 mm. The mechanical simulation of the clipping structure distortion under a 50N effort results in a total opening of 1,38 mm, far below the 4 mm diameter of the

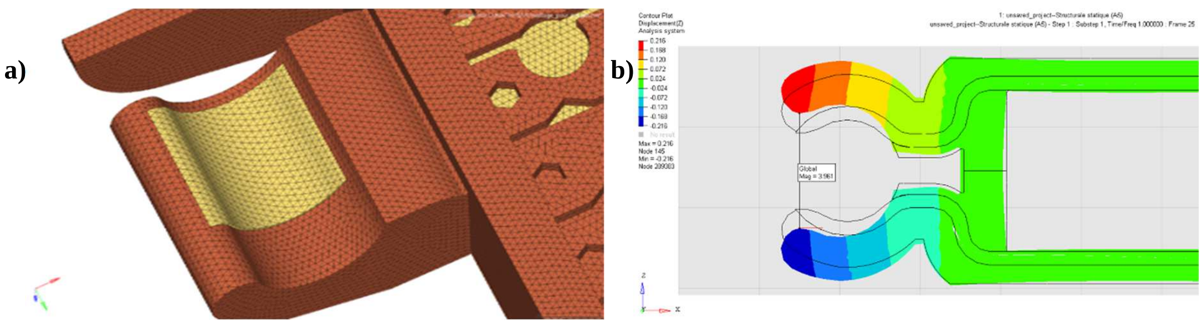

Fig. 4 (a) Meshed CAD design of the clipping structure, (b) mechanical simulation results

Fig. 5 CAD design for USB power bank packaging

copper cylinder. After increasing the initial gap of the clipping structure to 3 mm, and removing polymer material in specific areas (e.g. in the linking area between the round-shaped clip and the rectangular structure of the packaging) to achieve higher flexibility, the mechanical simulation results in a 3,96 mm opening (see Figure 4.b). This new configuration is selected for the final design of the packaging.

3.4. Li-ion cells connection inside the packaging

Within the packaging, Li-ion cells are connected to the overmoulded metal inserts in order to enable the electrical interconnection with additional modules. The mounting of Li-ion cells inside the package must fulfil both performances and safety requirements. To reduce potentially dangerous handling of the Li-ion cells with accessible electrodes, an alternative mounting solution is developed.
The individual Li-ion cells are electrically connected by soldering to a BMS, which integrates short circuit, overcharging and overdischarging functions. Pogo-pins are mounted on the BMS and are electrically connected to the Li-ion cells tabs. These pogo-pins provide the electrical contact with the overmoulded metal inserts during the packaging closure. Thanks to this solution, the metal inserts are electrically connected to the Li-ion cells only once the packaging is closed, reducing the risk for accidental contact by the operator. Using the spring effect of the pogo-pins, small variations in the position in height of the BMS are automatically compensated.

3.5. Dedicated packaging design for the USB power bank

An USB power bank has been designed in order to monitor and drive the interconnected battery cells. This electronic circuit is mounted in a dedicated packaging and integrates additional functions, in particular USB connectors in order to demonstrate the supply of electrical power to external devices.
The USB power bank is positioned at one end of the battery stack, connected with the assembled Li-ion cells using the same connector. Due to the size of the components, especially USB connector, the required packaging for the USB power bank is bigger than the Li-ion cells one, as depicted on Figure 5.

4. Connector design

To ensure low ohmic resistance <5 mΩ between cells and have a rotational degree of freedom of ±180° during assembly of the battery stack, a new connector concept is examined. Large area contacts with high mechanical flexibility made from copper foil are used for the internal connection. (Figure 6.a)
Injection molding is used for the connector housing, enabling economical manufacturing options. 3D-MID technology can be used for smart integration of sensors, eg. for temperature monitoring in the connector. For the smart variants of the connector, an LPKF-LDS® compatible LCP (Liquid Crystal Polymer) material is used. For connectors only implementing the core functionality of connecting the cells, a more economical polymer such as ABS/PC can be used.
Two connections for high current are formed by the connector in order to achieve parallel connection of cells. The concept can easily be adapted to implement serial connection of cells. (Figure 6.b)

a) b)

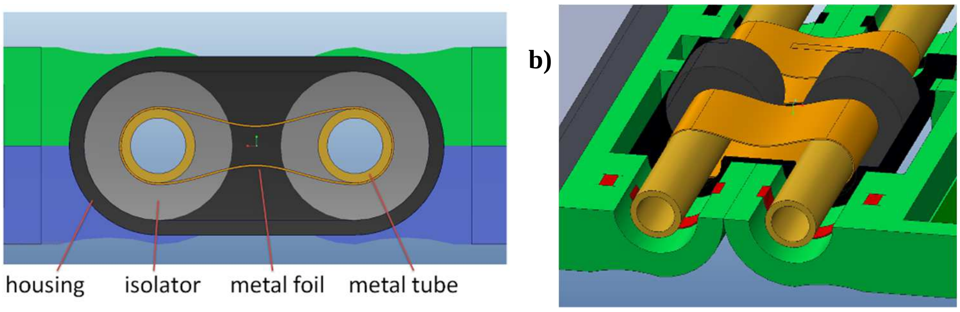

Fig. 6 (a) Cross section and (b) internal structure of the connector

Use of copper foil as connection material implies a wide range of possible surface finish options to ensure reliability and cost is fit to the desired field of application for the battery stack. Sn plated copper can be used for low requirements such as consumer electronics. Au or Ag plated copper can be used for fields of applications with higher requirements, such as automotive electronics.

5. Prototyping and manufacturing of the packaging

First prototypes of the packaging are fabricated using 3D printing technologies, and more specifically FDM (Fused Deposition Modeling) technology. A Voxel8 machine is used to manufacture functional packages, simultaneously depositing polymer material for the packaging structure and conductive ink for the electrical functions. This process enables the embedding of electrical and electronic functions in 3D-printed parts. PLA filament (polylactic acid, biopolymer widely used for 3D printing) and silver ink are used to manufacture the prototypes. These prototypes are used for design evaluation: no mechanical or electrical validation tests are performed on these parts.
Manufacturing of the final demonstrator is performed by injection moulding, and more specifically by overmoulding. This process is widely used in the polymer industry, but requires specific knowledge and know-how for a proper integration of the metallic inserts in the polymer part. The main challenge for such process is to control the flow of polymer in the insert area, in order to avoid the undesired covering of the conductive part in the functional areas.
The mould design is optimized in order to enable the correct positioning of the metal inserts within the mould cavity. Ejector pins are used as support for the inserts and blocking structures in order to avoid their displacement during the polymer injection phase. The cavities for the Li-ion cells and the USB power bank packaging are implemented in the same mould, for manufacturing cost optimization. The configuration for the injection can be easily selected: injection moulding of Li-ion cells packaging alone, injection moulding of the USB power bank packaging alone, or injection moulding of both packagings at the same time.
Overmoulding trials are performed using an Arburg Allrounder 370S 70 tons injection moulding machine. This equipment can be used in both horizontal and vertical configurations. The latter is preferred as it makes the handling and placement of the metal inserts in the mould cavity easier. The selected Bayblend T65XF ABS/PC material is dried at 110°C for 4 hours prior the injection moulding. Overmoulding process is performed with the parameters summarized in Table 2.

Table 2. Main process parameters for injection moulding of the packaging.

Process parameters	Value	Unit
Mould temperature	60	°C
Melt temperature	265	°C
Injection speed	40	cm^3/s
Injection pressure	1050	bars
Hold pressure	550	bar
Hold time	7	s
Cooling time	20	s

During the trials; the placement of the metal inserts in the mould is performed manually by the operator. This results in long cycle times (around 1 minute), which can be strongly reduced with the use of an automatic handling and placement of the inserts. The measured weight of the injection moulded Li-ion cells packaging is 17.8 g, very close to the above-mentioned 18.3 g estimation (Figure 7).

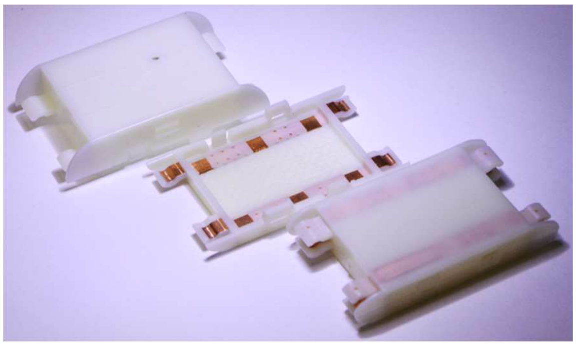

Fig. 7 Injection moulded packaging: UBS power bank half-packaging (left), Li-ion cell half-packaging (middle), and assembled Li-ion cell packaging (right)

6. Conclusion

An innovative polymer packaging and interconnection solution has been developed for Li-ion cells. Taking into account specifications related to electrical performances, mechanical performances and safety, the modular concept provides a suitable solution in order to improve the power-to-weight ratio of battery stacks. Light-weight individual packaging for Li-ion cells and USB power bank have been designed and manufactured by injection moulding. Future work will focus on the validation of the electrical and mechanical performances of the packaging, in particular with regard to UL1642 standard.

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7. References

EUROBAT E-Mobility Battery R&D Roadmap 2030 - Battery Technology for Vehicle Applications. Retrieved from https://eurobat.org/sites/default/files/eurobat_emobility_roadmap_lores_2.pdf

T. Zhang, I. de Meatza, X. Qi, E. Paillard, Journal of Power Sources, Volume 356, 15 July 2017, Pages 97-102

Rastikian, S., Eberhardt, W., Kück, H., Fuchs, S., Karamuk, E., Dessors, S., Fond, E., Legrand, J., Boubtane, M., Mbaye, M., Succoja, R., Forte, P., 2015. 3D-Hipmas : Pilot Factory for 3D High Precision MID Assemblies, Proc. Of 4M/ICOMM 2015 conference, Milan, Italy, paper 144.

Y.Berthe de Pommery, P. Azais, L. Picard, G. Turin, WO 2015 132192