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Effects of vibrations and shocks on lithium-ion cells

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HIGHLIGHTS

- We investigated how vibrations and shocks affect lithium-ion cells.
- Cells were stressed with UN 38.3 profiles as well as real-world vibrational loads.
- Cells with a tight packaging and fixed internal components showed no damages.
- Post mortem analyses and μCT revealed a loose mandrel for the tested 18650 cells.
- Depending on the direction of motion, the loose mandrel caused serious damage.

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ABSTRACT

Lithium-ion batteries are increasingly used in mobile applications where mechanical vibrations and shocks are a constant companion. This work shows how these mechanical loads affect lithium-ion cells. Therefore pouch and cylindrical cells are stressed with vibrational and shock profiles according to the UN 38.3 standard. Additionally, a vibration test is set up to reflect stress in real-world applications and is carried out for 186 days. The effects of the load profiles on the tested cells are investigated by capacity measurement, impedance spectroscopy, micro-X-ray computed tomography and post mortem analyses.

The mechanical stress has no effect on the investigated pouch cells. Although all tested cylindrical cells would pass the standard tests, in certain cells stressed in a vertical position the mandrel dispatched itself and struck against internal components. This caused bruised active materials, short circuits, a damaged current collector and current interrupt device.

The investigations are not directly transferrable to all pouch or cylindrical cells but show that the mechanical cell design, especially the fixation of the internal components, determines whether a cell withstands vibrations and shocks. Depending on the cell design and the loading direction, long-term vibrational loads can have additional detrimental effects on lithium-ion cells compared to standard tests.

1. Introduction

The demand for secondary batteries increased rapidly during the past decades and is likely to rise in the future. One cause for this is the sustained demand for portable electronic devices, such as tablets and cellular phones. The progressing electrification of vehicles will further boost the demand for secondary batteries [1]. Although lead-acid batteries will keep their high market share, lithium-ion batteries play an increasing role for mobile applications where mechanical stress is almost unavoidable [2]. In particular, mechanical vibrations and infrequent shock loads affect all parts of a battery including its smallest energy storing part, the accumulator cell, or short cell. Mechanical stress on cell level may cause market durability failures in the long-term and, especially for lithium-ion cells, these failures might pose a safety risk.

Although the effects of mechanical loads occurring in real-world usage on lithium-ion cells cannot be neglected, little research has been published on this topic. Moreover, mechanical tests proposed by standards aim to make only a pass-fail statement. Thereby cell behavior is only classified into failures, which can be seen from outside the cell, e.g. electrolyte leakage, or keeping functionality.

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This work aims to provide comprehensive knowledge on how standard vibration and shock tests as well as long-term vibrations affect lithium-ion cells. At the beginning, test standards regarding vibrational and shock loads are listed and compared to real-world load profiles. Because standard tests have to be carried out rather fast and aim to represent worst case scenarios, it is questionable whether the effects on cells caused by standard tests are the same as the effects caused by long-term real-world loads. Therefore, three test profiles are chosen for the experimental investigations presented in this paper:

- Sine vibrations according to the UN 38.3 T3 standard
- Mechanical shocks according to the UN 38.3 T4 standard
- Long-term vibrational test over six months with sine sweep vibrations based on real-world applications

In this work, lithium-ion cells of two cell designs, pouch and cylindrical, were tested with the three chosen load profiles. Thereby the possible directions of motion of the dynamical loads are investigated separately. While the cells were stressed with mechanical vibrations and shocks the cells remained at 50% state of charge (SOC) and no electric current was applied.

The tests were interrupted periodically in order to check the cells for possible degradations or failures. During the ongoing test period the cells should not be damaged. So, the cell status was determined by values, which were measurable by external sensors, such as the cell current, voltage or temperature. Before and after the testing, all cells were scanned with a micro-computer tomograph (μCT). After the mechanical load profiles had been finished, post-mortem analyses were carried out to get a deeper look into the changes and degradations that occurred inside the cells.

2. Vibrations and shocks in test standards and real-world applications

Various standards propose vibration and shock tests for lithium cells and battery systems. Table 1 lists the most common standards, which are explicitly designed for the testing of lithium-based accumulators on cell level.

The UN 38.3 is a standard for the safe transportation of goods. According to the definition in Refs. [3] and [4], lithium-ion cells are “miscellaneous dangerous substances and articles” classified class 9. Therefore, they shall be subjected to the UN 38.3 T3 vibrational test and UN 38.3 T4 shock test [4]. Cells fail the tests in case of mass loss, leakage, venting, disassembly, rupture or fire. Furthermore, the open circuit voltage may not drop below 90% of its initial value after the test [4].

Test procedures for lithium batteries which are used in products are defined in the UL 1642 standard. Cells pass the UL 1642 vibration and shock tests as long as they do not explode, catch fire, vent or leak [5].

The IEC 626602-2 standard defines reliability and abuse tests for automobile traction lithium-ion cells. No pass-fail criteria are provided but testing results should be classified in one of the following categories: no effect, deformation, venting, leakage, smoke, rupture, fire or explosion [6].

For all standards listed in Table 1, the evaluation of the tested cell's behavior is done by optical and electrical inspection only.

Furthermore, test procedures for cells in electric vehicles were proposed by the U.S. Advanced Battery Consortium (USABC), which include vibration tests with frequencies ranging between 10 and 190 Hz. In these tests, vibrations can either be random vibrations with an autospectral density of 0.1 g^2/Hz or swept sine vibrations with a maximum acceleration of 5 g [7].

For lithium-ion batteries in space applications, the NASA requires testing with random vibrations at frequencies between 20 and 2000 Hz with a peak acceleration of 13.65 g. In addition, the cells should be tested with shock loads at pyro-shock levels of 100–10000 Hz with up to 2000 g [8].

In Ref. [9] three battery electric vehicles (BEV) and one conventional vehicle with internal combustion engine (ICE) were tested on 13 different road surfaces. Vibrations were measured directly on each battery system. Significant vibration energy was measured within the frequency range of 0–7 Hz. Therefore, the authors concluded that the battery packs may be exposed to vibration loads outside the range of existing standards.

Measurements of accelerations occurring at the B-post in a BEV and a hybrid electric vehicle (HEV) were carried out in Ref. [10]. According to the measurements, a test profile for the battery system was derived, which comprises vibrations from 5 to 200 Hz with a maximum power spectral density of 0.48 g^2/Hz.

In Ref. [11] vibrations on the frame of bicycles with different suspensions were investigated, when driving on gravel surface and off-road tracks. The values measured at the bicycle frames are transferable to the battery and cells of an electric bicycle. Two frequency areas with accelerations of up to 13 g were identified, 0–100 Hz and 300–400 Hz.

When mobile electronic devices such as cellular phones are carried by a person in every day usage, vibrations with frequencies between 0 and 20 Hz with maximum accelerations below 1 g occur [12].

In summary, it can be ascertained that there is a deviation between the mechanical loads on lithium-ion cells proposed in standards and measured in real-world applications. This is because tests according to standards have to be carried out rather fast compared to the long-term usage of lithium-ion cells in real-world applications. Furthermore, standard tests often aim to represent worst case scenarios and consequently mechanical loads are higher and the frequency ranges are broader compared to those occurring in every-day usage. It is doubtful whether the intense tests according to standards cause the same effects on lithium-ion cells as the long-term loads in real-world applications.

This work aims to provide comprehensive knowledge on the effects of mechanical vibrations and shocks on lithium-ion cells. Therefore, the following three load profiles were chosen to stress the cells under investigation:

Table 1
Mechanical vibrations and shock loads on cell level in standards.

Standard	Application	Type of vibration	Frequency	Duration	Peak load
UN 38.3 T3 (IEC62281 T3)	Transport of lithium cells	Sine with logarithmic sweep	7–200 Hz	3 h	8 g
UN 38.3 T4 (IEC62281 T4)	Transport of lithium cells	Half sine shock	–	18·6 ms	150 g
IEC 62660-2 6.1.1.	Electric road vehicle	Random vibrations	10–1000 Hz	8 h	27.8 g
IEC 62260-2 6.1.2.	Electric road vehicle	Half sine shock	–	20·6 ms	50 g
UL 1642-16	Lithium cells and batteries	Harmonic vibrations	10–50 Hz	90–100 min	0.8 mm amplitude
UL 1642-15	Lithium cells and batteries	Shock	–	18 times	125–175 g