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Dynamic abuse testing of lithium-ion cells

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Summary

Special test benches for dynamic impact loading of charged and discharged battery cells were erected at the Fraunhofer Ernst-Mach-Institute in order to investigate the influence of strain rate and state of charge on the mechanical behavior of cells. Both parameters are regarded as of major importance for a comprehensive safety evaluation of electric vehicles.

The primary test bench is a special-purpose hydraulic machine which is set up in a safety environment so as to allow dynamic tests with fully charged real EV battery cells and modules. It provides a static force up to 500 kN and allows tests to be done in the velocity range between 0.5 mm/s and 5 m/s. A second complementary test stand is a commercial servo hydraulic machine, intended mainly for basic investigations on dynamic material properties and dynamic tests on small discharged cells. It offers a greater dynamic range, greater flexibility, and a higher force resolution compared with the bigger test stand. The combination of both test stands allows for detailed investigations of strain rate effects of battery cells.

First tests with both machines reveal a significant influence of the test velocity on the results of destructive mechanical tests of battery cells. These findings are of major importance for a realistic evaluation of battery crash safety. They provide important input for EV crash simulations and stress the necessity for dynamic tests in order to access realistic failure limits for battery cells.

Keywords: testing processes, safety, lithium battery, short circuit, crash

1 Introduction

Electrical energy storage devices are gaining increasing importance for propulsion technology as well as for temporary energy storage. However, the rising energy density of the available storage devices entails increased hazard potentials for users. Uncontrolled energy release can result in burn-out, poisonous gas development, or, in worst cases, the explosion of the whole entity. This is clearly demonstrated by an increasing number of documented accidents with Li-ion batteries [1, 2].

In spite of obvious safety risks of modern battery systems, an understanding of their complex failure mechanisms and loading limits is not available, for the time being. Up to now, crash safety issues have been dealt with mainly by using cells being in a low state of charge. Moreover, most tests were done quasistatically. Yet, only dynamic investigations on charged cells can provide meaningful conclusions about the risks of batteries in realistic crash szenarios.

In order to address this, a special-purpose test bench was developed and erected in a safety environment which allows dynamic investigations of fully charged Li-ion accumulators (test bench I). In conjunction with another smaller test stand (test bench II) intended for material studies and investigations of small discharged cells the possibility exists for a detailed analysis of strain rate effects in charged and discharged battery cells.

This paper gives a detailed description of the two tests benches and its data acquisition systems (chapter 2). In chapter 3 the installations devised for the protection of the test benches during dynamic tests are described. Chapter 4 presents the tested cell types and chapter 5 reports on results from dynamic intrusion tests performed over a wide velocity range. The focus is on tests with large pouch cells done with test bench II. Chapter 6 offers a preliminary discussion and outlook.

2 Test benches and data acquisition

Fig. 1 depicts photographs of the two test benches which are both servo-hydraulic machines. The larger battery test stand (test bench I, left side of Fig. 1) is situated in a bunker like environment offering full safety for tests with charged cells. It can be operated with cross head velocities between 0.5 mm/s and 5 m/s. Fully charged real EV battery cells and (small) modules can be analyzed in that test stand. During the tests the specimens are positioned in a steel test chamber situated on the base of the test stand and allowing harmful gases and particles to be filtered out. The test specimens can be loaded from above with different punches adapted to the cross head. The test bench allows for mechanical loading of test specimen with a quasi-static force of 500 kN. The dynamic forces may be more than twice as high.

The second test stand (test bench II) is a commercial machine. It works with a closed servo loop in the velocity range between 0.01 mm/s and 5 m/s, and offers a maximum (static) force of 120 kN. As only discharged cells and materials are used the test chamber here is made from acrylic glass.

In both test benches by default, loading strength, cell voltage, and punch displacement are recorded in every test. The punch's displacements are determined from the respective cross head displacements which were recorded in test bench II by an integrated inductive transducer and in test bench I by an external velocimeter. For the determination of the load/intrusion force in case of test bench II a piezo-electric load cell is adapted between piston and punch (see Fig. 3). In case of test bench I four strain gauges are attached to the piston in a multiple sensor setup which helps to reduce the influence of vibrations on the signal. In both cases, the setups were calibrated with a calibrated load cell before testing.

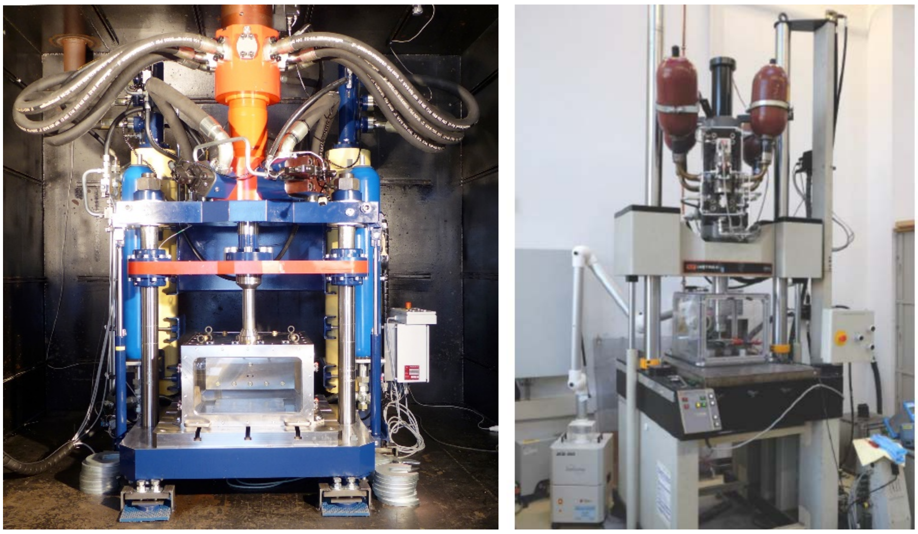

Figure 1: Photographs of the Battery test benches

3 Test procedure and force limitation devices

A principal difficulty when doing dynamic tests arises from the combination of high punch velocities in conjunction with relatively thin test specimens which are unable to absorb a substantial amount of energy. As a punch has to deform or penetrate a cells at least some millimetres to generate a short circuit and, additionally, 20-50 millimetres are needed for punch deceleration at higher testing velocities, a punch will penetrate or crush the cell completely and hit the surface beneath with considerable residual speed. This might cause significant damage to the punch, the force sensor, and/or the whole test stand. Especially with the bigger test bench I which features a considerable moving mass this is a critical issue. Thus, special force limitation devices were designed for both machines allowing tests to be done with full speed up to a maximum force and a free deceleration for higher loads. Generally the maximum force was set to be at least 3 times as high as the force to be measured.

As an example of a force limitation device, Fig. 2a gives the photograph of the device used with test bench II in punch penetration tests. The device here comprises two metal plates with central holes greater than the punch's diameter, a shear plate and a cylindrical piece of steel (Fig. 2b). The piece of steel fits into the hole of the upper metal plate and is kept in place by the shear plate beneath. By this, a flat bearing is provided for the cells under test. At the same time, the setup provides an upper limit for the force exerted onto the punch as the shear plate shears off when the shearing force is reached. If the force of the punch surpasses the shearing force of the plate, the steel piece falls to the ground and the punch penetrates the cell without further obstruction. This allows the punch to decelerate freely until its stop.

The shear force is determined by the plate's thickness and material and can easily be adjusted to lie well above the force to be measured and below any destructive value. We used pieces of steel panel for this purpose offering a shearing force of app. 15 kN per millimetre of thickness.

As an example, the punch shown in Fig. 2 has a spherical tip with a diameter of 12.7 mm and a length of 50 mm. This type of punch test is used frequently to characterize material properties of various battery cells for the development of finite element models and as a benchmark to compare the response of various cells [3, 4]. It may represent the intrusion of a bolt head into a battery during the deformation of a battery pack in an electric vehicle. From quasi static tests the critical force for short circuit generation with pouch cells was known to be around 10 kN [3, 4]. Accordingly, the shearing force of the punch base device was chosen to be around 30 kN well above the force to be measured.

Depending on test bench, punch geometry, cell casing, and the necessary force level for short circuit generation, different force limitation devices were designed and constructed. The maximum force limit applied in test bench I was 500 kN.

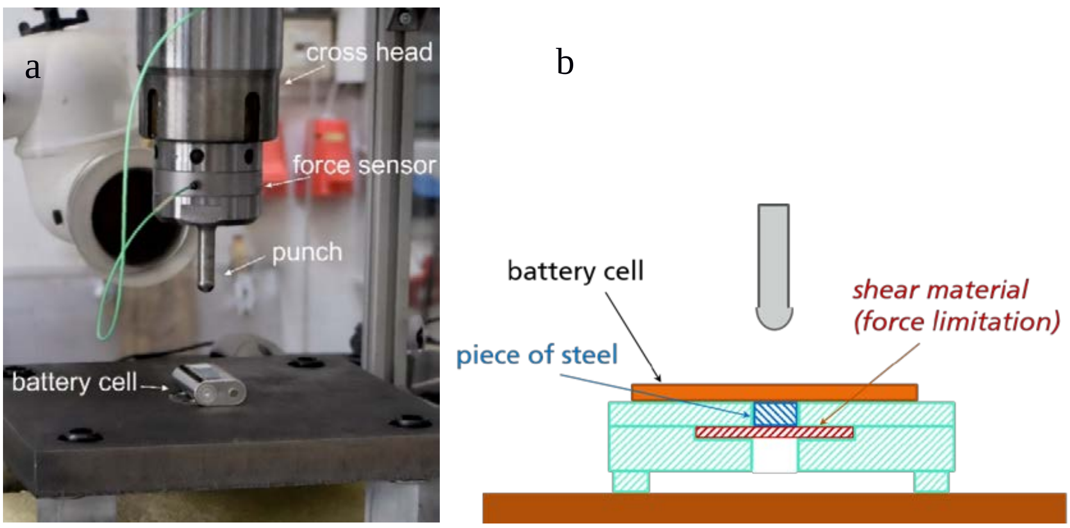

Figure 2: Experimental setup of the commercial test bench. a) Photograph with cross head, force sensor, punch, cell, and force limitation device, and b) Drawing showing the inner setup of the force limitation device.

4 Tested Battery Cells

Lithium-ion cells come in a variety of shapes and sizes. The main cell types in use are cylindrical, elliptical, pouch, and prismatic. Three of these types were tested dynamically on their susceptibility to intrusion and crush: prismatic cells, pouch cells, and small elliptical cells. The elliptical cell with a casing of thin aluminium had a length of 63 mm a capacity of about 5 Ah. These small and relatively cheap cells allowed a large number of tests to be done without too much inconvenience due to an almost negligible amount of harmful leakages. The elliptical cells were tested in test bench II, only.

As to the pouch cells, two different types were tested, which will be called pouch A and B. Pouch A had a capacity of ~ 30 Ah and dimensions of 225 mm x 225 mm x 7.2 mm. Pouch B came with a capacity of ~ 50 Ah and dimensions of 329 mm x 161 mm x 12.7 mm. These cells were tested in both test benches. Yet, the majority of tests were intrusion tests with uncharged cells and small punch geometries done in test bench II (section 5).

The prismatic cells were of type PHEV2. These cells were tested exclusively in test bench I. Crush and penetrations tests were done with discharged and charged specimens up to an SOC = 100 %. Although most of the respective results are confidential and may not be presented here, we emphasise that similar strain rate effects and comparable variations in critical values have been detected with large cells in test bench I as with small cells in test bench II.

Fig. 3 shows photographs of all cells tested so far. In preparation of the tests the cells were subjected to at least one full charge/discharge cycle in order to verify its nominal capacity.

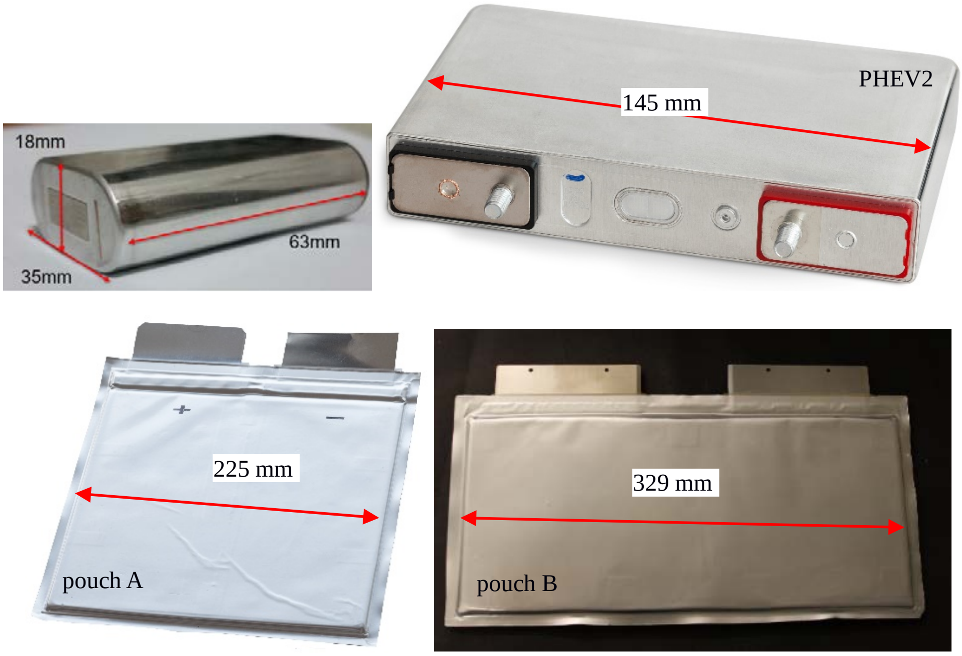

Figure 3: Photographs of tested cells. Upper row from left to right: small elliptic cell and prismatic PHEV2 cell, lower row from left to right: pouch cell A, and pouch B.

It is emphasized that due to inertia it is usually not possible to stop the crush/intrusion process immediately at short circuit. For example, in a high speed intrusion test cells become regularly completely pierced by the punch. Charged cells in addition catch fire or are further destroyed by chemical reactions. Hence, the cell condition and status around the point of short circuit emergence cannot be further analysed after a test. Fig. 4 depicts post-test pictures of three different cells. The prismatic cell (Fig. 4, right side) was tested with SOC = 100 % in test bench I. The other two cells with SOC = 0 % in test bench II.

Figure 4: Post-test photographs of cells. From left to right: elliptical cell, pouch cell B and prismatic cell. The prismatic cell was tested with SOC = 100%, the other two cells with SOC = 0%.

5 Exemplary results with pouch cells

Tests were performed with all cell types described in section 4. With every cell considerable influence of the test velocity on the results was found depending on punch geometry, cell form factor, and cell make-up. In this section exemplary results from intrusion tests with pouch cells are described. Additional information about these tests and comparisons with small elliptic cells can be found in [5]. Results from tests with large prismatic cells which are most relevant for electric vehicle safety evaluations will be published later.

All tests with pouch cells were intrusion tests with a small hemispherical punch seen in Fig. 2. During each test, load, displacement and voltage of cell terminals were recorded over time with a transient recorder. The recorder allows for data recordings with 12 Bit resolution at a maximum sampling rate of 10 MHz. For the tests sampling rates between 75 Hz and 500 kHz were used, depending on the overall intrusion time which varies with test velocity and cell thickness.

Fig. 5 depicts recordings from a test with a cross head speed of 5 m/s. Upon touching the cell surface, the force level first increases up to about 5 kN at an intrusion of ~ 2 mm, then the load breaks down to about 3 kN. Upon further penetration of the cell, the load level remains between 3 and 5 kN until the back side of the cell is reached. Next, the punch pushes against the back support of the cell and against the shear plate. This finally breaks at a load level of ~ 35 kN. The load at this point drops to zero. The punch comes to a rest about 20 mm after having reached the cell surface.

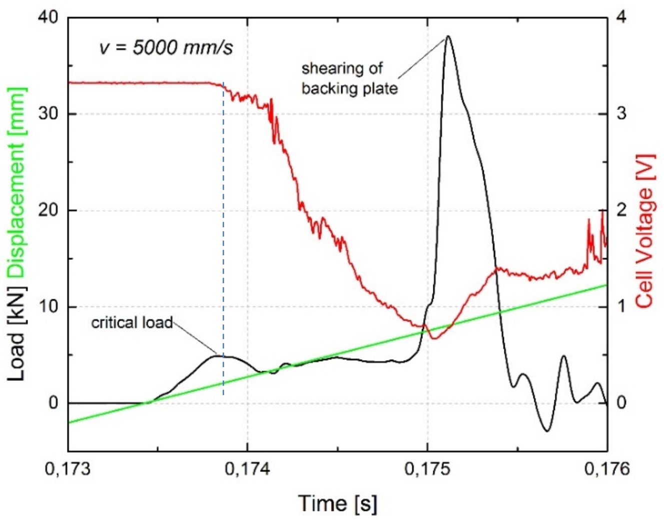

Figure 5: Load, voltage, and displacement time-histories of an intrusion test with a pouch cell of type B.

The cell failure time, i. e. the onset of short circuit formation, is determined by the beginning drop in voltage. From this, the critical load and critical punch displacement (intrusion) are identified which are of main importance for investigations of cell failure. Usually, short circuit formation occurs after a few millimetre intrusion, and the measurement could be stopped here in principle. Due to the inertia of the punch, however, the punch penetrates further into the cell which usually is completely pierced, as mentioned above. Nonetheless, as the shearing process is of no importance for this study the rear parts of the signal histories will not be shown in the rest of this paper. Only signals up and around the failure time will be presented.

The results of a test are most intuitively presented as load displacement curves where the load is displayed as a function of punch displacement (intrusion). For preparing these curves the measured cross-head displacement was carefully set to zero at the punch's impingement time on the cell which was determined by the rising edge of the load time history.

Fig. 6 depicts four such curves from tests with different velocities. The first picture reproduces the measurement of Fig. 5 around the failure time in higher resolution. Voltage here starts to decrease at about 2 mm intrusion when the load reaches a first maximum (critical load). With the pouch cells we found the first load maximum always to coincide with the beginning voltage drop. No significant voltage decrease was observed before the first load maximum was reached. It is upon puncturing of the cell that the voltage starts to decline.

A peculiarity of the pouch cells has been that there were several cases where the voltage did not drop to zero during a test at all. Rather the voltage remained at a slightly lower level. It is possible, hence, to pierce a pouch cell without causing a complete short circuit.

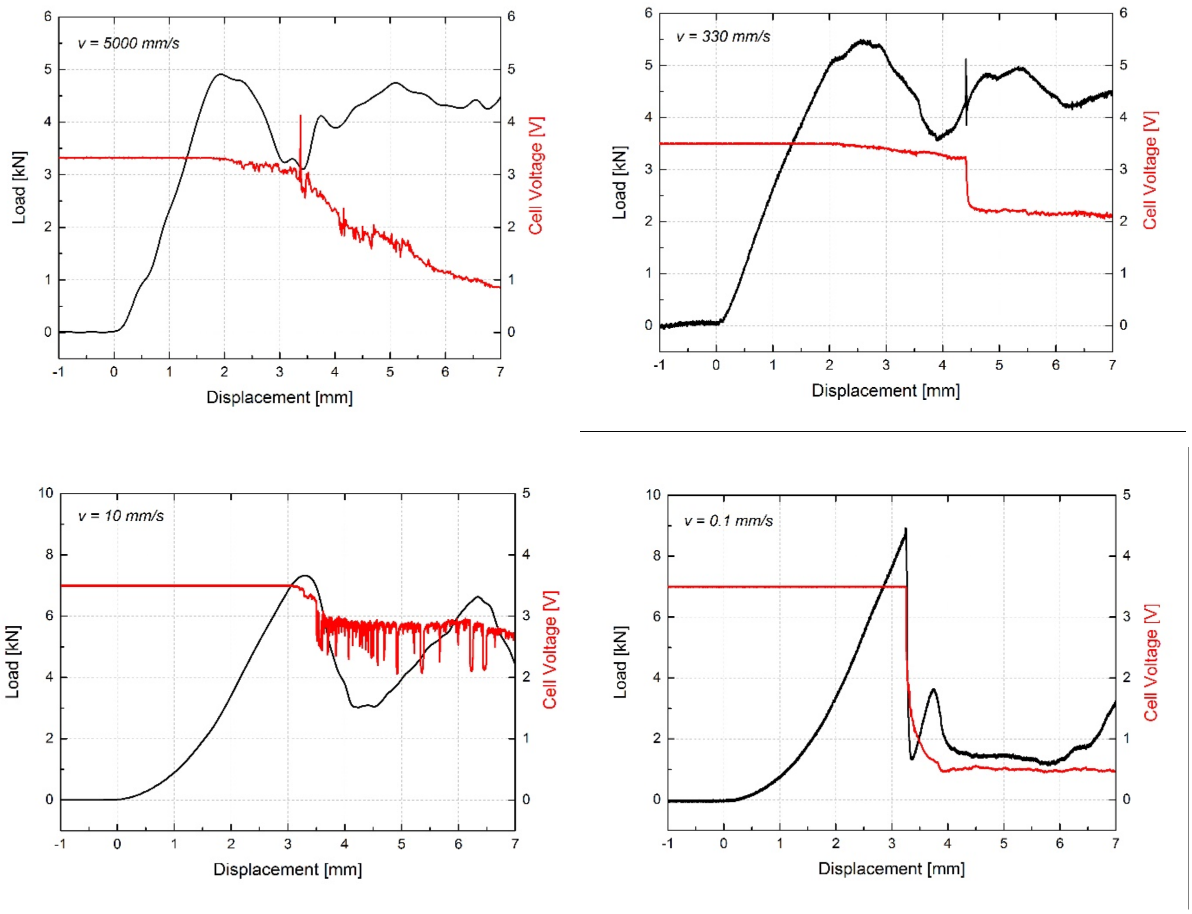

Figure 6: Load and voltage-displacement curves from intrusion tests with pouch cells of type B.

We did several tests with each single pouch cell, in order to increase the number of data points. This was possible because no significant differences in the load displacement curves of a new pristine cell and cells short circuited by a former test were found, at least not up to the time of the critical load. Additionally, the large area of the pouch cells allowed each cell to be pierced several times without interference between the different measurement areas. Of course, voltage and hence short-circuit information could only be registered with cells not being short-circuited. Hence, usually only one test per cell allowed a voltage-time history to be measured. Further tests, done with cells already short-circuited, provided load displacement recordings, only. This however does not constitute a disadvantage as the voltage drop coincides with the first load maximum. Up to four tests with a single pouch cell of type A and up to three with type B were done.

Fig. 7 gives the load displacement curves of two tests performed with v = 1 mm/s. The sharp voltage drop in the case of the pristine cell is accompanied by a sharp drop in load while the drop in force is more gradual in case of the previously short circuited cell. Yet, the rising edge of the curve and the peak load are almost identical.

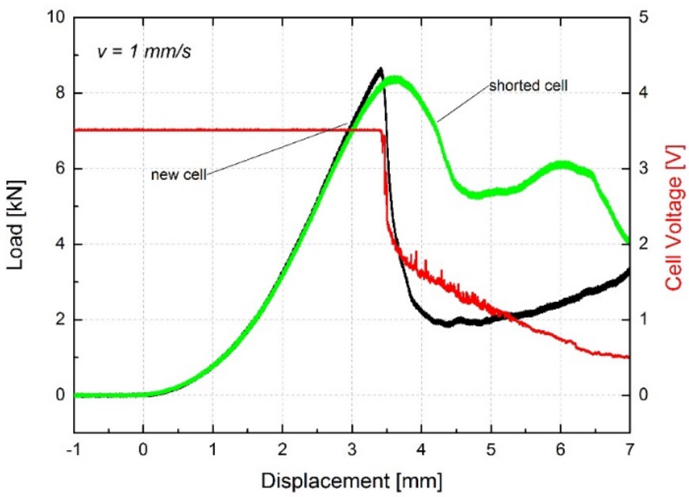

Figure 7: Load displacement curves for two tests both with v = 1 mm/s.

We had four cells of each type of pouch cell at our disposal. 16 tests with type A and 11 with type B cells were done. All tests have been evaluated as to the load and intrusion at the point of beginning voltage drop, denoted as critical load and critical intrusion, respectively. Fig. 8 (left) depicts the results for the critical load as a function of velocity for both kinds of pouch cells. Both types, apparently, reveal the same behaviour. The critical load drops by a factor of approximately two in the tested velocity range. All results made with active cells, i.e. cells with a voltage signal, are marked with a cross. Note that five measurements from each cell type could be performed with an active voltage signal because in each case one cell did not develop a permanent short-circuit in the first test and could be used with voltage signal a second time.

In Fig. 8 (right) the critical intrusion is shown as a function of velocity. It decreases by a factor of approximately two as well. The two dotted lines are least square fits to the data points. The two fits result in almost identical slopes for both kind of pouch cells. Yet, the absolute values of critical intrusion for pouch B are about one millimetre higher than the ones for pouch A. This probably is related to the different cell thicknesses, pouch cell A being about 60 % thinner than pouch cell B.

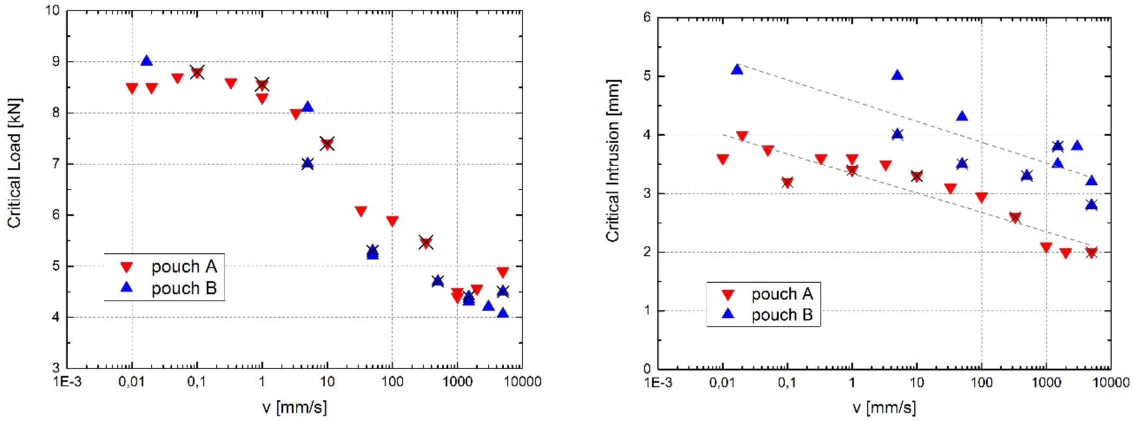

Figure 8: Critical load and critical intrusion for both types of pouch cells tested. Tests made with active cells are marked with a cross. The other tests were made with cells already short-circuited from former testing. The lines on the right picture are least square fits to the data points.

In Fig. 9 load displacement curves from different test velocities with pouch A cells are presented. These cells seem to harden at higher velocities as the curves steepen with increasing velocity. Nevertheless, critical intrusion depth and critical load decrease as apparently an increased brittleness of the material counteracts to the hardening effect.

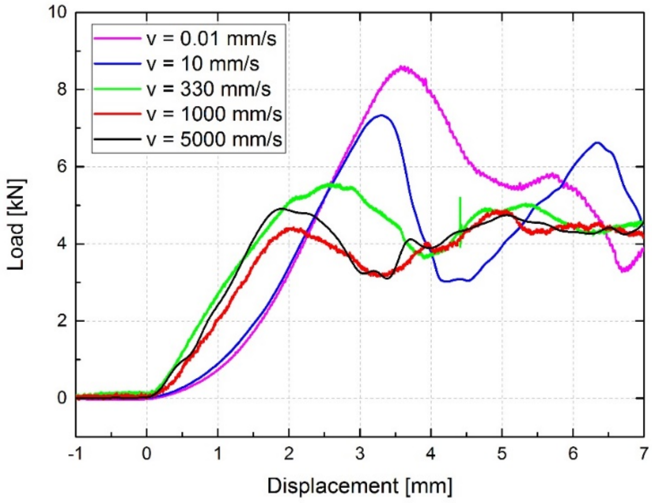

Figure 9: Load displacement curves for pouch cells of type A for different punch velocities.

6 Summary and Conclusion

Dynamic local indentation tests have been performed in the velocity range between 0.01 mm/s and 5 m/s. With two different types of pouch cells, it was demonstrated that the critical force necessary to generate an internal short drops roughly by a factor of two from almost 9 kN to nearly 4 kN in the tested velocity range. The decrease in critical load is an interesting feature of the dynamic response of pouch cells. It renders the cell more susceptible for failure at higher intrusion velocities than in the quasi-static range. This behaviour is both counter intuitive and difficult to explain.

These findings are important for a realistic evaluation of battery crash safety, as they indicate that the failure limit of battery cells should be estimated in dynamic rather that quasi-static tests.

By now the ongoing research focusses on intrusion tests with pre-defined intrusion. This is done with mechanical gadgets which trigger a force limitation at a predefined punch displacement. We hope to be able to give more detailed analysis of the cell status right before short circuit generation in this way.

The data provide important input for EV crash simulations and stress the necessity for dynamic tests in order to access realistic failure limits for battery cells.

Acknowledgments

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References

[1] Q. Wang, P. Ping, X. Zhao, G. Chu, J. Sun, C. Chen, *Thermal runaway caused fire and explosion of lithium ion battery*, J Power Sources 208 (2012), 210–224

[2] BBC News Technology, *Authorities investigate after Tesla car catches fire*, http://www.bbc.com/news/technology-37104753, accessed on 2017-02-13

[3] Sahraei E, Hill R, Wierzbicki T. Calibration and finite element simulation of pouch lithium-ion batteries for mechanical integrity. J Power Sources 3201 (2012) 307–321

[4] Sahraei E, Meier J, Wierzbicki T. Characterizing and modeling mechanical properties and onset of short circuit for three types of lithium-ion pouch cells. J Power Sources 247 (2014) 503–516

[5] T. Kisters, E. Sahraei, T. Wierzbicki, Dynamic Impact Tests on Lithium-Ion Cells, Int. J. Impact Engineering, (2017), in press

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Thomas Kisters is working as a scientist at the Measurement and Sensor Technology Division of the Fraunhofer Ernst-Mach-Institute (EMI) in Germany. He received a Diploma in physics from the University of Göttingen and a PhD from the University of Hannover. His current research focuses on high-speed measurement techniques and dynamic battery testing. Other interests are sensor development and blast investigations.