

Mechanical Behavior of Lithium-Ion Battery Component Materials and Error Sources Analysis for Test Results

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ABSTRACT

As mechanical damage induced thermal runaway of lithium-ion batteries has become one of the research hotspots, it is quite crucial to understand the mechanical behavior of component materials of lithium battery. This study focuses on the mechanical performance of separators and electrodes under different loading conditions and the error sources analysis for test results. Uniaxial tensile tests were conducted under both quasi-static and dynamic loading conditions. The strain was acquired through the combination of high speed camera and digital image correlation (DIC) method while the force was obtained with a customized load cell. Noticeable anisotropy and strain rate effect were observed for separators. The fracture mode of separators is highly correlated to the microscopic fiber orientation. To demonstrate the correlation microscopic images of separator material were obtained through SEM to match the fracture edges of tensile tests at different loading directions. Coated electrode materials show higher fracture strength and higher elongation compared to decoated materials in uniaxial tensile tests. Electrode materials show relatively slight strain rate effect, and no apparent anisotropy was found in their test results. An error analysis program was developed through MATLAB to estimate the standard uncertainty of the results. Input quantities such as initial dimensions of specimen and measured load, fast Fourier transform (FFT) of acquired data and deviation of repeated measurements were taken into consideration as main error sources. Contribution of these sources was evaluated and the results turn out that the low-order magnitude of external force and dimension lead to high level FFT smoothing uncertainty and measurement uncertainty, respectively.

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INTRODUCTION

Due to its high energy density and power density, lithium-ion batteries have been widely applied on electric devices and play a major role in energy supply of electric vehicles. In terms of full scale battery modules or packs, researches focused on the safety issue of lithiumion batteries under different mechanical loading conditions have been conducted. Feng et al. [1] studied the thermal runaway propagation of large lithium-ion battery module by penetrating the first battery and concluded that penetration induced thermal runaway can be triggered at a lower temperature in such a case compared with the results of thermal runaway tests using accelerating rate calorimetry with uniform heating. Lamb et al. [2] conducted penetration on small modules of cylindrical and stacked pouch cells, it turned out that the thermal runaway was less likely to be triggered for cylindrical cells when a single cell failed. Finite element models of lithium-ion battery packs were built to study the crash response of battery packs and the crashworthiness of electric bus [3, 4].

Researches on the correlation between mechanical damage of a single cell and the internal short circuit (ISCr) were also promoted. A coincident drop of loading force was observed when ISCr occurred in the indentation, compression and indentation tests on pouch cells and cylindrical cells conducted by Sahraei et al. [5, 6]. Shape and material of the punch head also influence the occurrence of ISCr in battery

cells [7, 8]. Cai et al. [9] designed a stroke-return pinch tests to study the ISCr of lithium-ion and lithium-ion polymer cells, indicating that a lower stroke-return voltage and a higher state of charge (SOC) increase the risk of thermal runaway. A torsion component superimposed on pinch loading can reduce the required axial load to trigger ISCr with smaller short spot size, and the SOC dependence of thermal runaway risk varies with the type of separator.

Lithium-ion battery is an assembly of stacked or wound electrodes and separators. The key to precisely predict ISCr of battery cells is to well understand mechanical behaviors of these materials. A crushable foam model was found to be appropriate to simulate the response of jellyroll of lithium battery as a homogeneous material under predominantly compressive loads [5, 6, 7, 10]. Confined and unconfined in-plane compression response of representative volume element (RVE) was analytically studied in [6, 11, 12, 13, 14] and RVE was observed mechanically anisotropic under those load types. Separator damage is considered to be the major reason that causes ISCr. Researches on mechanical performance of separators were carried out. Temperature and strain rate dependence of separator was studied in [15], where uniaxial tensile tests were conducted under a strain rate range from 0.001/s to 0.1/s and a temperature range from 28.5°C to 80°C, indicating strong temperature dependence and strain rate effect - tensile strength increases with strain rate and decreases

with of temperature. Luo et al. [8] performed uniaxial tensile tests on separators in two types of lithium batteries under different strain rates. It was observed that the elongation ratio decreases and the tensile strength increases apparently with strain rate for both separator types. Meanwhile the strong anisotropy of mechanical properties was observed for the separators. However, materials in different battery types could present strain rate effect and anisotropy in different ways. Sheidaei et al. [16] investigated the tensile behavior of a single layer polypropylene (PP) separator in electrolyte solutions for lithium-ion batteries using a dynamic mechanical analyzer (DMA), and it turns out that the mechanical properties of the separators are significantly lower under wet condition, indicating that the mechanical properties measured under dry condition using samples preconditioned in electrolyte solutions are not sufficient to represent in situ material behaviors.

In the present paper, uniaxial tests of separators, electrodes and Al-plastic films taken from pouch battery cells were conducted under quasi-static and dynamic conditions. One more direction between the transverse and longitudinal direction was tested to study the anisotropy of separators and Al-plastic films. Microscopic images of separator were obtained through SEM to study the mechanism of different fracture modes. Influence of coating on electrode materials and strain rate effect were studied. Error sources were analyzed by referring to [17], in which errors were divided into measurement uncertainty, FFT filter uncertainty and repeated tests uncertainty. As all the tested materials were thin films with thickness no more than 0.2mm, contribution of the error sources was different from that for traditional automotive metal sheets as presented in [17]. Analysis of error contribution can help our future work to improve the test accuracy.

EXPERIMENTS

Material Information

All the specimens were dissembled from a batch of battery cells of the same model from an electric car. The separator is one kind of polymer, but the detailed specification was not provided out of commercial reasons. The electrode materials are composed of electrode current collectors sandwiched by two layers of active electrode coating. The anode collector is copper foil, and the cathode collector is aluminum foil. The ingredients of electrode coating were not provided either. The material of cell pouch is Al-plastic film. The material information is listed in Table 1. A digital spiral micrometer with increment of 1 μ m was used to measure the thickness of a stack of 10 pieces of materials for 10 times. The overall average value was adopted.

Table 1. Material information and specimen thickness

Component	Material	Thickness (mm)
Separator	Polymer (specification concealed)	0.0286
Anode	Sandwiched composite	0.1780
Anode current collector	Copper foil	0.0114
Cathode	Sandwiched composite	0.1735
Cathode current collector	Aluminum foil	0.0233
Cell pouch	Al-plastic film	0.1560

Specimen Dimensions and Preprocessing

Dimensions of tensile tests specimen are shown in Figure 1. All the specimens for tensile tests were prepared in this shape. The dimensions is chosen according to the fixture of the test machines.

A set of tools shown in Figure 2 was designed to guarantee the identical gauge lines and the speckled region rightly in the middle of a specimen. Figure 2(a) displays all the components. The base (A) contains eight slots with which eight specimens at most can be preprocessed one time. A pair of metal blocks (B) are used to fix one specimen as shown in Figure 2(b). The metal frame with wider arms (C) leaves a window for drawing identical gauge lines on specimen as shown in Figure 2(b), while the metal frame with slimmer arms (D) leaves a window for spraying speckles on the specimen for digital image correlation (DIC) as shown in Figure 2(c). The regions not speckled are strengthened by adhesive tapes to keep failure from these regions. Figure 3 shows the preprocessed specimens of different materials.

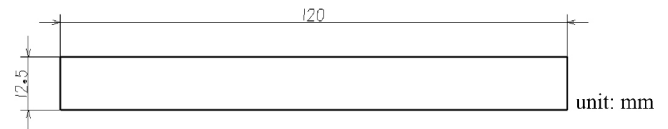
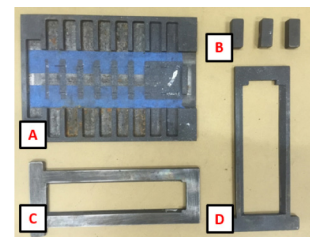
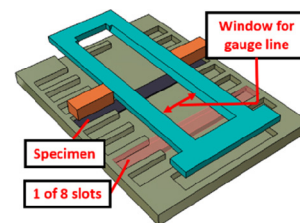


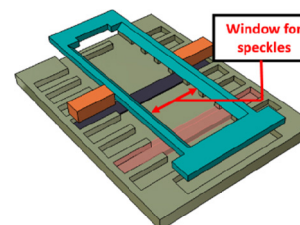
Figure 1. Specimen dimensions.



a.

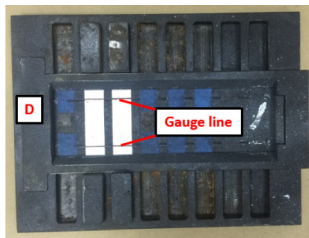


b.



c.

Figure 2. Tools to guarantee identical gauge lines and speckled regions in the middle of a specimen: (a) all the components (A - base, B - metal block, C - gauge line window, D - speckled region window), (b) the use for drawing gauge lines, (c) the use for spraying speckles, and (d) the real photo for tools and specimen in use.



d.

Figure 2. (cont.) Tools to guarantee identical gauge lines and speckled regions in the middle of a specimen: (a) all the components (A - base, B - metal block, C - gauge line window, D - speckled region window), (b) the use for drawing gauge lines, (c) the use for spraying speckles, and (d) the real photo for tools and specimen in use.



a.



b.

Figure 3. Preprocessed specimens: (a) separator, and (b) Al-plastic film.

Experimental Condition

Strain rate and specimen orientation considered in testing of each component material are listed in Table 2. 0° is defined as the width direction of pouch cell which is parallel to the fiber direction of the separator. Separator and cell pouch materials were tested at three directions, while all electrode materials were tested at two directions. Dynamic strain rate of all specimens reached 33 s^{-1} , corresponding to a loading speed of 1 m/s . Quasi-static strain rate of electrode materials was 0.00018 s^{-1} , corresponding to a loading speed of 0.5 mm/min . The separators were tested at two strain rates (0.0036 s^{-1} and 0.019 s^{-1}) under quasi-static loading condition, corresponding to loading speeds of 10 mm/min and 50 mm/min . Only dynamic tests were conducted on cell pouch material.

Quasi-static tensile tests were conducted on a 2.0 kN Zwick universal testing machine. Industrial CCD was used to record images of deformed speckled pattern at the rate of 4 fps , and these images were processed by DIC to extract strain data afterwards.

Table 2. Loading rate and specimen orientation

Component	Orientation	Strain rate (s^{-1})
Separator	0° 45° 90°	0.0036 0.019 33
Anode sandwich	0° 90°	33
Anode current collector	0° 90°	0.00018 33
Cathode sandwich	0° 90°	33
Cathode current collector	0° 90°	33
Cell pouch	0° 45° 90°	33

Dynamic tensile tests were conducted using a hydraulically driven intermediate strain rate test machine (refer to [18, 19]). The deformation in dynamic tension was recorded by high speed camera and a frame rate of $67,500 \text{ fps}$ was adopted. The force was measured using a customized load cell [20] and the force signal was filtered by fast Fourier transform (FFT) smoothing to reduce noise. The load cell was calibrated on a CRIMS DDL50 universal testing machine. The setup of dynamic tensile tests was shown in Figure 4. Strain data was also extracted with DIC method in dynamic tests.

Microscopic images of separator were obtained using a scanning electron microscope (SEM), Model HITACHI S5500, to analyze mechanism of different fracture modes under tensile loading.

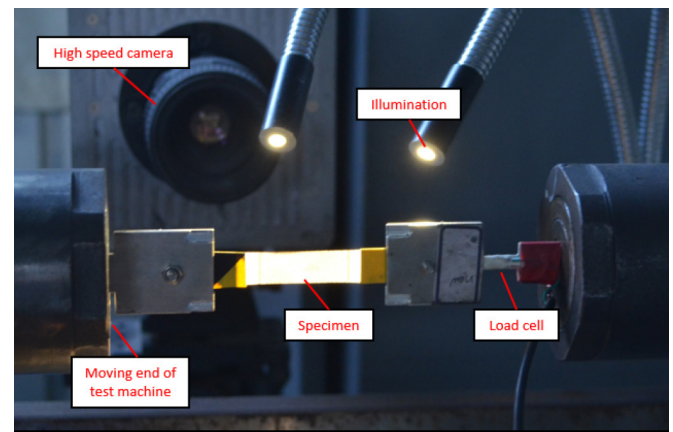


Figure 4. Setup of dynamic tensile test of separators

TEST RESULTS AND DISCUSSION

Separator specimens were prepared along three directions and tested at 3 strain rates. Figure 5(a) to Figure 5(c) display the nominal stress versus nominal strain curves of separators along different orientations at 0.0036 s^{-1} , 0.019 s^{-1} and 33 s^{-1} , respectively. Figure 6(a) to Figure 6(c) display the nominal stress versus nominal strain curves at different strain rates along 0° , 45° and 90° orientations of the separator, respectively.

Remarkable anisotropy can be observed from Figure 5, and with increase of strain rate the anisotropy becomes more obvious. The tensile strength along 0° is much higher than those of 45° and 90° at each strain rate. Under quasi-static loading condition, the deviation of strength between 45° and 90° separators is less than that between 0° and 45° , presenting a slighter anisotropy. The deviation of elongation ratios between different orientations becomes larger as strain rate increases. The elongation ratios at the strain rate 0.0036 s^{-1} are almost identical to one another, whereas at the strain rate 33 s^{-1} the elongation ratio along 0° becomes one-third of that along 90° , and the elongation ratio along 45° becomes half of that along 90° .

Figure 6 demonstrates an apparent strain rate effect of the separator material along all the three tested material orientations. Strain rate effect along 45° and 90° is a little less significant than that along 0° .