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# Failure analysis of pinch–torsion tests as a thermal runaway risk evaluation method of Li-ion cells

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## HIGHLIGHTS

- Finite element models are developed to evaluate the effectiveness of the pinch–torsion test in creating ISCrs in Li-ion cell.
- The torsion component can trigger ISCr at a lower load with smaller short spot size.
- This method can distinguish commercial cell safety performance in their entire range of SOC.

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## ABSTRACT

Recently a pinch–torsion test is developed for safety testing of Li-ion batteries. It has been demonstrated that this test can generate small internal short-circuit spots in the separator in a controllable and repeatable manner. In the current research, the failure mechanism is examined by numerical simulations and comparisons to experimental observations. Finite element models are developed to evaluate the deformation of the separators under both pure pinch and pinch–torsion loading conditions. It is discovered that the addition of the torsion component significantly increased the maximum first principal strain, which is believed to induce the internal short circuit. In addition, the applied load in the pinch–torsion test is significantly less than in the pure pinch test, thus dramatically improving the applicability of this method to ultra-thick batteries which otherwise require heavy load in excess of machine capability. It is further found that the separator failure is achieved in the early stage of torsion (within a few degree of rotation). Effect of coefficient of friction on the maximum first principal strain is also examined.

## 1. Introduction

Lithium-ion batteries are becoming a primary power source in our daily lives through electronic devices (cell phones, tablets and laptops) and transportations (hybrid and electric vehicles, and airplanes). These applications are demanding more power output, higher power density and lower cost, sometimes at the expense of safety. Safety hazard related issues of Li-ion cells have been well documented [1,2]. Many major field incidents are caused by externally or internally (e.g., manufacturing defects, mechanical abuse, usage abuse, etc.) induced short circuits, which can potentially release the high energy stored in the battery in very short time locally and trigger chemical chain reactions releasing a massive amount of heat. If the battery is not well designed such that the heat cannot be conducted away quickly, thermal runaway could happen and lead to fires and explosions in some extreme cases [3,4]. Among these safety concerns, internal short circuit (ISCr) under no obvious abuse or external triggers are less understood and very difficult to reproduce experimentally. Therefore, evaluating the thermal runaway risk of Li-ion batteries by experimentally creating ISCr in a controllable and predictable manner has brought broad interests to the field.

In order to evaluate the risk of thermal runaway, many tests have been conducted to simulate ISCr event via internal defect initiation, including forced ISCr test by the Battery Association of Japan [5], instrumented indentation [6,7] and nail penetration [8].

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**Nomenclature**

| | |
|---|---|
| $a$ | contact radius |
| $c(\theta)$ | distance between the maximum tangential traction location and the contact center |
| $F_0$ | the applied load on the indenter in pinch only test |
| $h$ | the thickness of cathode, separator, and anode layers in the unit cell |
| ISCr | internal short circuit |
| $M_z$ | the twist moment applied on the indenter |
| $p(r)$ | normal contact pressure distribution in the contact area |
| $q(r)$ | tangential traction in the contact area |
| $r$ | distance to the contact center in the contact area |
| $u_1$, $u_2$, $u_3$ | displacements respectively in $x$, $y$, $z$ direction in Fig. 2 |
| $u_4$, $u_5$, $u_6$ | rotations respectively along $x$, $y$, $z$ direction in Fig. 2 |
| $\varepsilon_0$ | the maximum first principle strain in pinch only test with the load $F_0$ |
| $\varepsilon_{\mathrm{I}}$ | the first principal strain |
| $\varepsilon_{\mathrm{I}_{\max}}$ | the maximum first principal strain |
| $\varepsilon_{\mathrm{III}}$ | the third principal strain |
| $\varepsilon_{\mathrm{Y}}$ | yield strain |
| $\theta$ | twist angle |
| $\mu$ | friction coefficient |
| $\sigma_{\mathrm{Y}}$ | yield strength |
| $\sigma_{\mathrm{u}}$ | ultimate strength |

We recently reported an improved pinch test method [9,10] that could reproducibly create controllable ISCr in a cell separator where the size of the ISCr spots depends on the loading speed, pinch ball or indenter diameter, and stroke return-voltage. A further development of this pinch test method added a torsional loading component, which exhibited improvement in the effectiveness of creating the ISCr [11]. It was demonstrated in two different commercial Li-ion cells that the torsion facilitated the occurrence of ISCr with lower axial load and smaller ISCr spot size. This method is thus potentially applicable to very thick batteries, for which the critical loads under pure pinch tests are too large for the standard loading apparatus.

In order to quantitatively relate the pinch–torsion tests to the thermal runaway failure in batteries, it is of critical importance to understand the deformation and failure mechanisms under such loading conditions. For instance, what is the dependence of the critical normal/twist load on the indenter radius, battery thickness, number of electrode/separator layers, and indenter/battery friction condition, among many other factors? Imagine an application of successive pinch and torsion loads, and one can design the loading pattern/history to conveniently identify the failure initiation and optimize the load magnitude to allow a portable evaluation. Motivated by the above considerations, the present paper attempts to develop a computational model for both test methods (pinch-only and pinch–torsion test systems) and make a systematic investigation on the deformation mechanisms to provide insight for the battery safety assessment. In this paper, finite element method (FEM) is used to simulate the strain field and to predict the defect initiation, which was then compared with experiment results. The effect of surface condition was also discussed to optimize the test design. Moreover, the deformation mechanisms were rationalized by an analytical stick-slip model when both contact and torsion were applied.

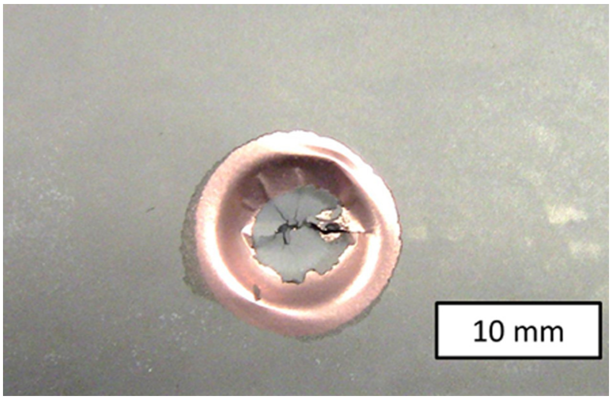

**Fig. 1.** Optical graph of an anode layer after pinch testing showing most of the graphite coating in the indented region was removed during the test (the gray zone is graphite coating).

## 2. Numerical model

The repeating functional unit of a dry Li-ion cell contains an anode layer, a cathode layer, and a separator layer. Since electrolytes used in most Li-ion cells are in liquid phase, they are not included in the finite element models. In addition, the active coatings (graphite and lithium salts) are generally loosely bonded powders on the electrodes. During slow pinch–torsion tests, the coating materials were delaminated, worn into small pieces and displaced from the highly stressed zone near the indenter tip. In fact, our experimental observation revealed that the active coating materials were pushed away from the contact area after testing (Fig. 1). Therefore, the coatings structurally bear little load especially comparing with the other components and will be simply excluded in our model. The stress equilibrium equation is $\partial\sigma_{ij}/\partial x_i + b_j = 0$ in which $b_j$ is the body force and is ignored in our model. The strain $\varepsilon_{ij}$ are the first derivative of the displacement i.e. $\varepsilon_{ij} = \frac{1}{2}(\partial u_i/\partial x_j + \partial u_j/\partial x_i)$ [13] and stress–strain relationship is given by the constitutive laws which will be discussed later. The boundary value problem is then resolved with commercial finite element package ABAQUS (3DS SIMULIA).

Fig. 2 depicts a three-layer (anode–separator–cathode) unit cell model in the FEM simulation in this study. The material of the top anode layer is Cu, the separator layer in the middle is high-density polyethylene (HDPE) and the bottom cathode layer is Al. The thickness of each layer $h$ is 0.02 mm. The two indenters in the pinch and torsion test are modeled as two rigid spheres and the indenter radius is 12.7 mm. The lateral dimension of the unit cell (~10 mm) is chosen to be ten times larger than the estimated contact radius

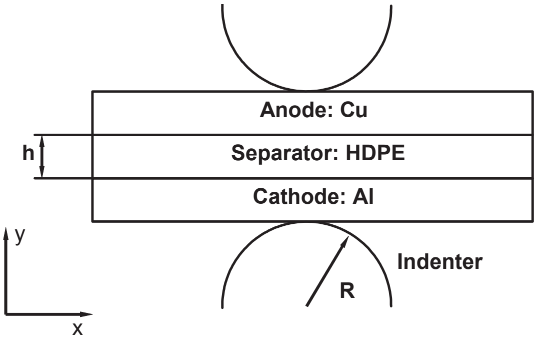

**Fig. 2.** Schematics of the cross section view of a three-layer battery unit cell system under the pinch tests between two spherical indenters.