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Review article

A review of safety-focused mechanical modeling of commercial lithium-ion batteries

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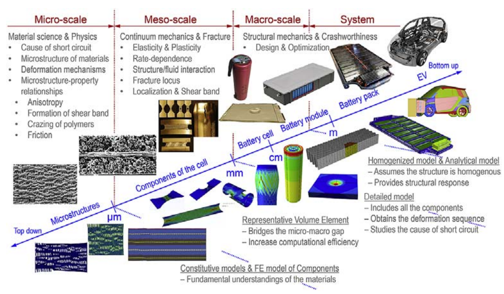
HIGHLIGHTS

- Recent progresses in the safety-focused mechanical modeling of LIBs are reviewed.
- Multi-scales: micro/meso (material), macro (cell), and macro-system (module, pack).
- Reviewing detailed/homogenized/RVE FE models, material models, & analytical models.
- Experiments at component/cell/module levels are summarized.

GRAPHICAL ABSTRACT



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ABSTRACT

We are rapidly approaching an inflection point in the adoption of electric vehicles on the roads. All major automotive companies are having well-funded plans for mass market affordable branded EV product line models, which can open the floodgates. A rapid growth of battery energy density, accompanied by an aggressive progress of reduction of costs of lithium-ion batteries, brings safety concerns. While more energy stored in the battery pack of an EV translates to a longer range, the downside is that accidents will be more violent due to battery inevitable explosion. With today's technology, severe crashes involving intrusion into the battery pack will potentially result in a thermal runaway, fire, and explosion.

Most of research on lithium-ion batteries have been concerned with the electrochemistry of cells. However, in most cases failure and thermal runaway is caused by mechanical loading due to crash events. There is a growing need to summarize the already published results on mechanical loading and response of batteries and offer a critical evaluation of work in progress. The objective of this paper is to present such review with a discussion of many outstanding issues and outline of a roadmap for future research.

1. Introduction: study of mechanical properties of LIBs at multiple scales

The market of Electric Vehicles (EV) is no longer a matter of speculation and analysis predictions. The introduction in 2017 of Chevy Bolt and Tesla Model 3 marks a new era for the automotive industry. Both cars have over 200 miles range on a single charge and are affordable. According to the comprehensive report of the UBS [1], the cost parity of gasoline engine and EV will be reached 2–3 years earlier than originally believed. This trend is mostly due to the advances in the design of lithium-ion batteries in terms of energy capacity and simultaneous drop in the price of a battery pack.

The annual production of Tesla 3 is expected to reach 500,000 units while the output of GM's Bolt will be slightly less. All new Nissan Leaf

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Nomenclature

E	Elastic modulus
ν	Poisson's ratio
$\bar{\varepsilon}_p$	Plastic strain
$\dot{\bar{\varepsilon}}_p$	Plastic strain rate
ε_{22}^p	Plastic strain in the transverse direction
ε_{33}^p	Plastic strain in the thickness direction
r_L	Lankford r-value
MD	Machine direction
TD	Transverse direction
DD	Diagonal direction
f	Yield function
$\sigma_{ij}(i, j = 1,2.3)$	Stress component
$\bar{\sigma}_Y$	Equivalent flow stress, function of plastic strain
F, G, H, L, M, N	Coefficients of Hill48 yield function
σ_0	Yield stress
Q, β	Coefficients of Voce hardening law
η	Stress triaxiality
$\bar{\theta}$	Lode angle parameter
c_1 and c_2	Coefficients of Modified Mohr-Coulomb model
a and n	Coefficients of the power law
C	Coefficient of Johnson-Cook model
$\mathbf{E}$	Total strain tensor
$\mathbf{E}^e$, $\mathbf{E}^p$	Elastic and plastic strain tensor
μ	Friction coefficient of Drucker-Prager model
ϕ	Friction angle of Drucker-Prager model
c	Cohesion parameter of Drucker-Prager model
p	Pressure, first invariant of deviatoric stress
q	Mises equivalent stress, second invariant of deviatoric stress
r	Third invariant of deviatoric stress
$\mathbf{S}$	Deviatoric stress
ε_f	Normalized critical displacement (NCD) to short circuit
δ_f	Displacement to short circuit
l_c	Characteristic length in the loading direction
p_0	Center of the yield ellipse on the p-axis of crushable foam model
A	Size of the yield ellipse on the p-axis of crushable foam model
B	Size of the yield ellipse on the q-axis of crushable foam model
Φ	Void volume fraction of Gurson-Tvergaard-Needleman model
P	Load measured in abuse tests of cells
H_c	Thickness of cell
R	Punch radius in hemispherical punch test
N	Total number of electrodes in a cell
h_f	Thickness of current collector
m	Number of waves in the length
D	Bending rigidity of a plate

with 150–200 miles range will be available on the market in 2018. Altogether, the total stock of EV, which already crossed one million mark in 2016, is reaching now an inflection point. The International Energy Agency [2] predicts that by 2025, there will be up to 100 million cars on the roads world-wide. With such a large number, the law of statistics will apply and EV will experience a similar number of accidents as the gasoline-powered cars. The question that must be posed and answered is what new safety issues bring the EV as compared to the gasoline-powered cars.

It is generally recognized that if the battery pack is split-open or damaged in the accident, there is a potential of the so-called battery thermal runaway, fire, and explosion. The highly-publicized accident of

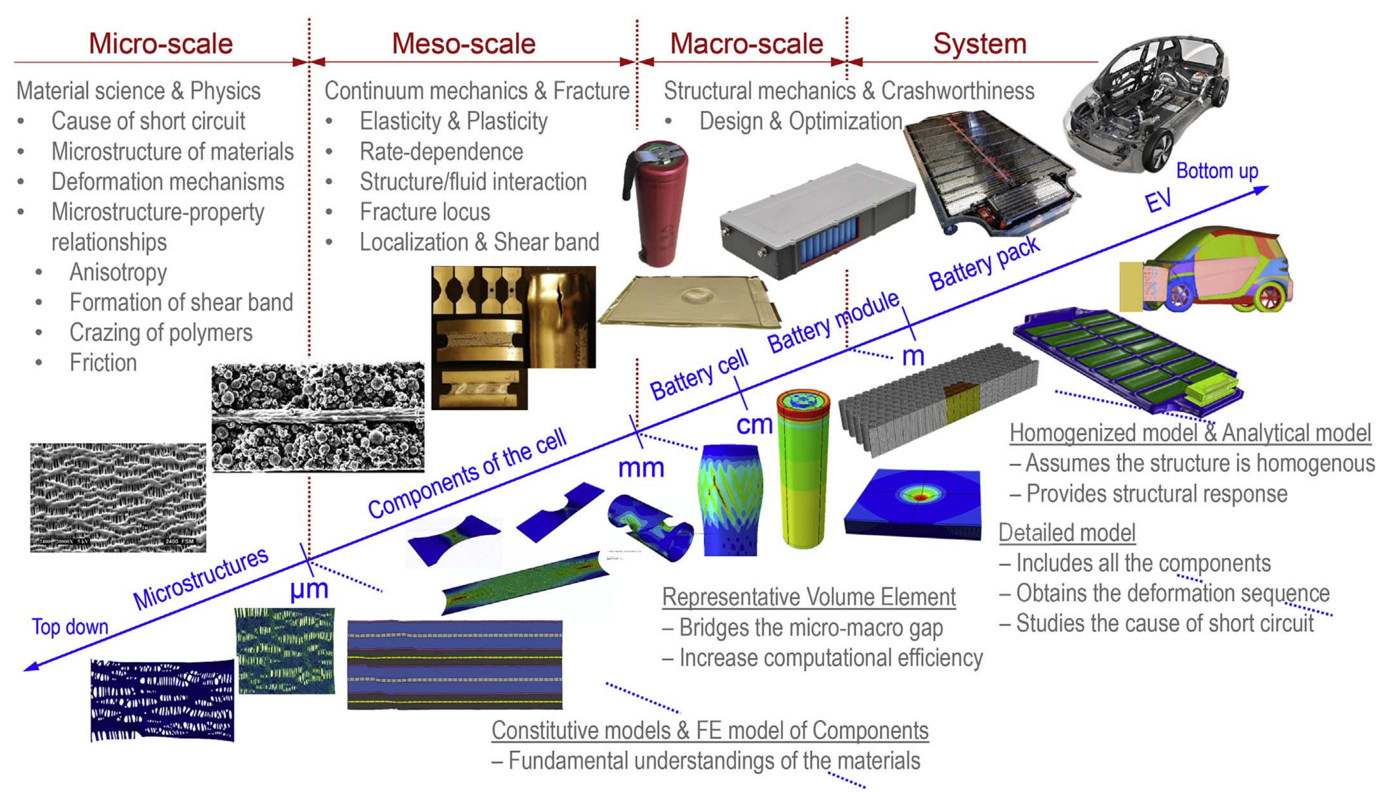

Fig. 1. The study of mechanical properties of LIBs involves multiple scales and disciplines, and various models have been proposed to characterize the mechanical behavior of LIBs at each length scale.