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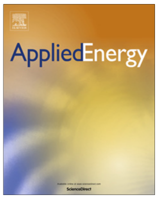

Clay-like mechanical properties for the jellyroll of cylindrical Lithium-ion cells

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HIGHLIGHTS

- The mechanical properties of the jellyroll are found clay-like.
- A validated finite model for the jellyroll was established.
- The model accurately predicts the mechanical behaviors of the jellyroll.
- Proposing micro stress area to reveal the constitutive behaviors of individual components of the jellyroll.

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ABSTRACT

In this investigation, several quasi-static mechanical tests on cylindrical Lithium-ion battery cells are performed to reveal the essential mechanical properties of the jellyroll. Utilizing the plastic flow rule, it was found that the homogenized mechanical properties of the jellyroll are similar to the clay (clay-like). According to the mechanical characteristics of clay, a linear equation was proposed to describe the nonlinear constitutive behavior of the jellyroll. An explicit finite element model for the jellyroll that could accurately predict its mechanical response during deformation using crushable foam constitutive behavior was established in HyperWorks/LS-DYNA to validate the proposed approach. The simulation results of various loading cases are in good agreement with the corresponding experimental results. By proposing a micro stress area, the stress-strain relations for components of the jellyroll were calculated individually. A finite element model was developed to compare the mechanical properties of the jellyroll by changing the thickness of different components, including the metal foils and the active particles. The simulation results indicate that the change of the thickness of the coating active particles will influence the mechanical properties of the jellyroll.

1. Introduction

The unique characteristics of electric vehicles make them an effective solution to the problem of energy, environment and climate change with respect to urban traffic. They represent a developing trend of the automobile industry, which includes zero release, wide energy sources, high efficiency, low vibration noise and so on [1–7]. Lithium-ion battery cells are the primary batteries used in electric vehicles due to their obvious advantages, such as high energy density, high specific power and long cycle life [8–13]. With the rapid popularization of electric vehicles, the safety and reliability of the Lithium-ion battery systems have been a focus of the automotive industry. Recent safety accidents have especially increased the concerns from consumers about the safety of electric vehicles and slowed their further popularization.

Except for the normal Li insertion/removal reactions on the anode and cathode, a series of side reactions happening at different temperatures are hidden inside different components of the Lithium-ion battery cells, which will release considerable heat [14–18]. Once used in an unsafe range, such as extreme load or internal short circuits caused by defects produced during manufacturing process, these side reactions may be triggered and lead to thermal runaway and even ignition. Therefore, improving the safety of Lithium-ion battery cells is crucially important.

Currently, the safety of Lithium-ion battery systems is mainly improved through engineering designs and optimization techniques [19–21]. These include improving the structural crashworthiness of the car body and battery box to avoid or decrease the

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Nomenclature

p	average principal stress	R	original radius of the battery
q	generalized shear stress	w	vertical displacement
H	applied load	L	length of the cell
σ	normal stress	b	contact width
τ	shear stress	F	force
λ	plastic ratio	S	micro stress area
f	plastic potential function	ε_i^p	equivalent strain
σ_i	equivalent stress	ε_{av}	average strain
σ_{av}	average stress	E	Young's modulus
σ_f	tensile cut-off value	v	elastic Poisson ratio
ρ	density		
ε	strain		

damage to the battery system during accidents. Abuse tests to evaluate the safety of Lithium-ion battery cells only provide binary pass/fail results, which do not provide more technical information that could aid in the design of battery cells. Better knowledge of the mechanisms causing internal short circuits under mechanical load could provide mechanical parameters for the design of the cells, cell components or the battery box and can decrease the risk of short circuits, the following thermal runaway or ignition under extreme load.

Individual Lithium-ion battery cells consist of a jellyroll, which is packaged by a hard steel or aluminum shell casing. The jellyroll is composed of several identical single cells that are wrapped or stacked inside the casing, depending on the shape of the battery, which include pouch, cylindrical and prismatic shapes. Each single cell is composed of five layers: aluminum foil, anode, polymeric separator, cathode and copper foil. The anode and cathode are a mixture of active particles that are coated on the surface of the foils [22]. However, there is no adhesive between layers of electrode/separator assembly.

Extensive research has been carried out to study the mechanical properties of individual components of the battery cells under different conditions. Sheidaei et al. investigated the tensile behavior of a single layer of polypropylene separator in both dry and wet conditions for both the machine and transverse direction [23]. They found different conditions affected the mechanical properties and a very strong tendency towards anisotropy. Chen et al. also researched the mechanical behaviors of microporous polymer separators [24,25]. Wierzbicki et al. investigated the mechanical properties of the shell casing and end-caps of 18,650 Lithium-ion cells [26]. They concluded that the contributions from the shell casing and end-caps to resist deformation could be neglected, compared with the jellyroll. Xiao et al. used a finite element based multiscale approach to analyze the stress of the separator in a battery cell [27]. Zhang et al. utilized a set of simulation techniques to systematically study the intercalation-induced stresses developed in particles of various shapes and sizes [28].

The mechanical properties of the entire battery cell under different loading conditions were investigated by several authors. Sahraei et al. performed mechanical tests on pouched and bare Lithium-ion cells under five loading conditions and developed an FE model of an individual cell based on these calculated stress-strain curves from the measured data [29]. Wierzbicki et al. developed a hybrid experimental/analytical approach to extract the average mechanical properties of cylindrical Li-ion cells and built a finite element model to closely predict the kinematic behavior of the cell during different loading cases [26]. Gilaki et al. developed and compared two homogenization methods for the jellyroll in a cylindrical Lithium-ion battery cell [30]. Based on the results of the homogenization, a simulation model was developed to predict the mechanical response of a cylindrical Lithium-ion battery cell when subjected to impact testing. Greve et al. performed a quasi-static mechanical abuse test program on cylindrical Lithium-ion battery cells at a 0% state of charge [31]. A macro-mechanical finite element crash simulation model has been established for the cell housing and the jellyroll. The classical Mohr-Coulomb criterion has been applied to predict fracture and initiation of an internal short circuit of the jellyroll. Jun Xu et al. established an anisotropic homogeneous model of the jellyroll and validated it through compression, indentation, and bending tests at quasi-static loadings [32]. Some research has revealed that the change of the state-of-charge (SOC) will influence the mechanical properties of the active particles [33,34] and the entire battery [32].

There have been numerous efforts to study the cell behavior after short circuit initiation. Maleki et al. investigated internal short circuits on the thermal stability of Li-ion cells of various sizes using a combination of experimental methods and thermal modeling [35]. They found the location of the internal short circuit plays a critical role in the consequences of an internal short circuit event. Fang et al. developed a 3D (Three-Dimensional) electrochemical-thermal model to study internal short circuits in a Li-ion cell [36]. They concluded that the heat accumulated during the initial stage is the key factor that determines the consequence of an internal short. Feng et al. proposed a model-based estimation algorithm to track internal short circuit incubation status or to detect instantaneously triggered internal short circuits [37]. Spotnitz et al. described a simple approach for using accelerating rate calorimetry data to simulate the thermal abuse resistance of battery packs [38].

In this investigation, the clay-like mechanical characteristic of the jellyroll was revealed through a hybrid analytical/experimental approach. A corresponding finite element model was developed to validate the proposed approach, which could be used to accurately predict the deformation behavior of the jellyroll under various loading conditions and the inside stress state of cell during deformation. This model makes it possible to ensure the mechanical safety limits of battery box and the deforming situation of battery cells inside the box during a crashing simulation of the entire vehicle. Then, the constitutive behaviors of components for the jellyroll were found based on the assumed micro stress area. A finite element model was then established to compare the mechanical properties of the jellyroll by changing the thickness of different components, including the metal foils and the active particles. The simulation results account for the evidence from one side, that the change of the state-of-charge (SOC) will influence the mechanical properties of the active particles and the entire battery. These parameterizations also provide some important information for the design of the jellyroll in terms of safety.

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