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Fracture mechanics modelling of lithium-ion batteries under pinch torsion test

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ABSTRACT

For the design of batteries to sustain the crash tests, the mechanical strength (force generated) on the battery can be evaluated to understand its fundamental effect on possible failure (such as breaking of separator and short-circuit) of batteries. In this perspective, this study proposed a holistic approach to evaluate the maximum force generated on the battery when subjected to the pinch-torsion test. The fundamentals of the test are understood by formation of Finite element analysis (FEA) model and validated based on experiments. The inputs in FEA such as the temperature, the displacement and the strain rate are varied and the maximum generated force is observed on the battery. The quantification of the finite element data is further performed by an optimization approach of GP. It was found that the GP model for an evaluation of mechanical force on the battery is accurate. The robustness in the model is validated by design of its simulation for 10,000 runs. 2-D and 3-D surface analysis suggests that the displacement due to indentation is the most dominant followed by the temperature and the strain rate. The findings from the analysis can pave the way for design of new battery that comprises of higher strength when subjected to the crash tests.

1. Introduction

Most of the current electronics devices such as mobile phone, laptop and electric vehicles have widely been using Lithium-ion battery (LIB) as the energy storage system since it offers a high energy storage density [1–4]. There has been an unprecedented increase in energy density of LIBs due to progress of the electrodes materials and the growth of cell assembling methods [5]. Furthermore, LIB has other advantages such as no memory effect [6], longer lifespan [7], eco-friendliness [8] and low self-discharge [9]. Although LIB has a high energy density, it is prone to thermal runaway risks [10,11]. As a consequence, maintaining a high level of safety standard to match the accelerating energy density is a serious task to achieve.

The thermal runaway risks in LIB are generally evaluated by simulating an internal short circuit (ISCr) in the LIB using standard tests. These standard tests involve subjecting the LIB to external loading conditions such as indentation [12], nail penetration [13], pinch test methods [14], etc. By investigating the deformation and failure mechanism of LIB under these loading conditions, it is possible to quantitatively relate the thermal runaway risk caused due to external mechanical abuse of the LIB. In order to understand the deformation behaviour of LIB, various studies in relation to LIB performance under loading have been conducted. Brand et al. [15] investigated the effects of mechanical loads to LIB by conducting a vibration test to duplicate stress in real-world applications. It is concluded that the negative effects created by external mechanical loads due to vibration can be overcome by fabricating tightly packed battery components. Amiri et al. [12] proposed an indentation technique for which can be used for investigating the mechanical performance of LIB. This method was useful to analyse the elastic modulus of LIB components which cannot otherwise be predicted by standard tensile loading tests. Wang et al. [16] also utilized the indentation technique to analyse mechanical deformation of LIB cells. It is found that one of the potential causes for short circuit caused by mechanical indentation could be the narrowing of separator. In addition to above, Xu et al. [17] conducted experimental studies on LIB under both bending and compression loadings. It is found that state of charge (SOC) is significantly related to the mechanical performance of LIB. Avdeev and Gilaki [18] proposed a different experimental method in which high- speed camera and computer tomography were used to capture and characterise the nonlinear mechanical deformations in LIB. This method is particularly useful in capturing information regarding the areas of LIB which have possible

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electric shortages. By far, all of these findings have obtained the relationship of mechanical loading to the performance of LIB through experiments.

In addition to above experimental studies, simulation studies have also been conducted to simulate the failure mechanisms of LIB under a variety of loading conditions. Ashwin et al. [19] simulated the capacity of LIB under cyclic loading. Their studies assert that the development of solid electrolyte interface layer and battery life is found to be influenced critically by the diversity of porosity and the convective heat transfer coefficient. Ali et al. [20] created mathematical models for simulating the representative volume element specimens of LIB cells under in-plane confined compression tests. These models recognise the impacts of the friction between components of the cell and the confined surfaces on the load displacement curve, plastic deformation, void compaction and the deformation pattern. Subsequently, Zhou [21] created a model that induces stress into the LIB electrodes by taking into account the impacts of outside mechanical loading. It is concluded that the external mechanical loading generates a major effect on the development of stresses created in the electrode. Moreover, Xu et al. [22] developed an anisotropic model to explain the mechanical reactions of the LIB when the battery is bended, indented and under compression loadings. Additionally, Amodeo et al. [23] developed a mathematical model under in-plane confined compression tests which showed that quasi-static loading states have lower nominal stress at huge nominal tension compared to those under dynamic loading situations.

All of the mentioned methods above have shown positive prospects of characterising LIB under mechanical loading. However, ISCr under no apparent maltreatment or outside prompts are very hard to create experimentally and less comprehended. To address this problem, pinch-torsion test [24,25] was developed in which the torsion component is combined with compression loading of LIB indentation test. This triggers ISCr at a lower load with smaller short spot size. The SOC of LIB under pinch-torsion test is directly related to the maximum resistive force which the LIB can withstand. The maximum force of LIB is affected by various factors such as operating temperature, indentation depth, strain rate etc. It is hence useful to model the maximum force of LIB as a function of dominant factors which can help in identifying the initiation of LIB failure and optimizing the mechanical load for a stable LIB design.

In view of the above research gap which has been highlighted, it would be interesting to develop a holistic approach that can evaluate the maximum force of the battery under pinch-torsion test for a wide range of dominant factors as can be seen in Fig. 1. The battery model built using the holistic approach shall be able to explain the fundamentals and estimate its strength in uncertain input conditions. Therefore, the present work shall propose the holistic approach based on finite element-genetic programming (GP) approach. The research problem of evaluation of maximum force of battery is described in Section 2. The finite element procedure involving the modelling of maximum force of lithium-ion battery is described in Section 3. Section 4 introduces the battery modelling approach based on the GP algorithm. Section 5 provides the statistical analysis of the GP based maximum force model of the battery. Section 6 discusses the robustness of the model in uncertain input conditions. Finally, Section 7 concludes with the implications arising from the current study.

2. Research problem on maximum force of battery

This section discusses the problem statement on evaluation of maximum force of the battery. Fig. 1 shows the problem formulation on modelling the twist load of a three layer (anode-separator-cathode) module of LIB under pinch-torsion test. The battery is subjected to external torsion and displacement which results in generation of an opposing force which is chosen as the output in our study. The force is influenced by operating temperature, indentation depth and strain rate. The mechanics of deformation of LIB module under the considered input factors are modelled systematically by using commercial FE software. The FE model is further complemented by GP algorithm which is applied to quantify the accurate relationships between the mechanical strength (force) and the three inputs and to evaluate its robustness in uncertain conditions. The extrinsic/intrinsic factors such as the shocks/vibrations could introduce unsystematic variations in the temperature, number of electrode/separator layers, and radius of indenter, which can thus significantly affect the battery strength estimation.

3. Description of finite element model

The deformation mechanics of LIB under pinch-torsion test is modelled by deploying FE technique by considering the effects of operating temperature, number of modules and radius of indenter. The commercial FE software, ABAQUS/Explicit Version 6.14 with fully coupled thermal stress analysis was used for constitutive modelling of plastic deformation of LIB module. This kind of analysis is particularly useful in understanding the mechanics of plastic behaviour of LIB module undergoing thermal runaway risks. This study considers the three-layer module of LIB which has been used earlier by Xia et al. [25] for the simulation purposes of FEM. The minor components of LIB such as the isolators, jelly roll, casing, etc., does not undergo much deformation and are hence excluded in this model. Furthermore, the electrolyte of LIB is also neglected in FE simulation since it mainly consists of liquid paste.

Fig. 2 shows the unit cell of LIB consisting of three layers, viz. the anode, separator and cathode. Copper is considered as the anode, the high-density polyethylene (HDPE) acts as the separator and aluminium as the cathode. The dimension of each layer in the FE model is

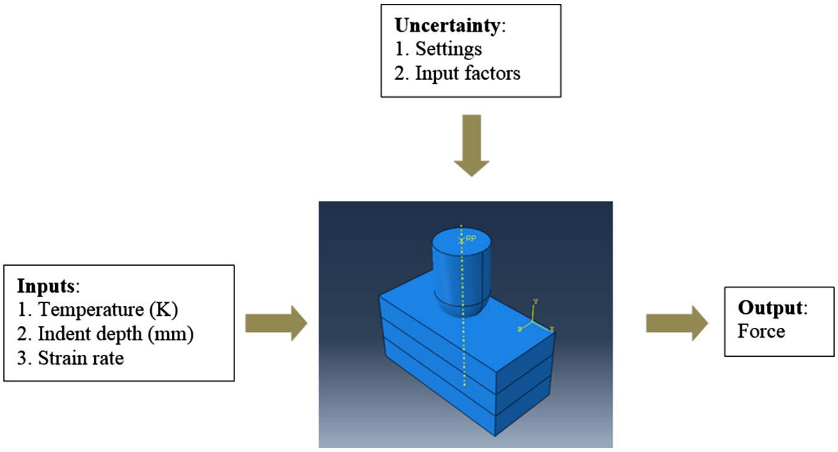

Fig. 1. Modelling of mechanical strength of LIB under pinch-torsion.