

Jay Carroll · Shuman Xia · Allison M. Beese · Ryan B. Berke
Garrett J. Pataky *Editors*

Fracture, Fatigue, Failure and Damage Evolution, Volume 6

Proceedings of the 2018 Annual Conference on
Experimental and Applied Mechanics



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and Applied Mechanics

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Preface

Fracture, Fatigue, Failure and Damage Evolution represents one of the eight volumes of technical papers presented at the 2018 SEM Annual Conference & Exposition on Experimental and Applied Mechanics organized by the Society for Experimental Mechanics and held in Greenville, SC, June 4–7, 2018. The complete Proceedings also includes volumes on *Dynamic Behavior of Materials; Challenges in Mechanics of Time-Dependent Materials; Advancement of Optical Methods & Digital Image Correlation in Experimental Mechanics; Mechanics of Biological Systems & Micro-and Nanomechanics; Mechanics of Composite, Hybrid & Multifunctional Materials; Residual Stress, Thermomechanics & Infrared Imaging, Hybrid Techniques and Inverse Problems; and Mechanics of Additive and Advanced Manufacturing.*

Each collection presents early findings from experimental and computational investigations on an important area within experimental mechanics, fracture and fatigue being one of these areas.

Fatigue and fracture are two of the most critical considerations in engineering design. Understanding and characterizing fatigue and fracture has remained as one of the primary focus areas of experimental mechanics for several decades. Advances in experimental techniques, such as digital image correlation, acoustic emissions, and electron microscopy, have allowed for deeper study of phenomena related to fatigue and fracture. This volume contains the results of investigations of several aspects of fatigue and fracture such as microstructural effects, the behavior of interfaces, the behavior of different and/or complex materials such as composites, and environmental and loading effects. The collection of experimental mechanics research included here represents another step toward solving the long-term challenges associated with fatigue and fracture.

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Chapter 1

In Situ Strain Measurement in Solid-State Li-Ion Batteries

B. Koohbor, L. Sang, Ö. Ö. Çapraz, A. A. Gewirth, R. G. Nuzzo, S. R. White, and N. R. Sottos

Abstract Volumetric changes due to repeated lithiation and delithiation are a significant source of electrode degradation and capacity fade in rechargeable batteries. Measurement of such volumetric changes and their resultant electro-chemo-mechanical strains and stresses have previously been investigated in conventional liquid-electrolyte Li-ion batteries. In the present study, we propose to extend the current knowledge and measurement techniques into the area of all-solid-state Li-ion batteries. Due to the presence of inherent property mismatch as well as confinements imposed at the interfaces between the electrodes and solid electrolyte, solid-state battery components are more prone to interfacial damage and. In this work, novel experimental approaches are designed to facilitate in-situ strain measurements on solid electrolytes (SE), electrodes and SE/electrode interface. Digital image correlation (DIC) is utilized to enable full-field strain measurements.

Keywords Solid-state battery · *In situ* strain measurement · DIC · Electrode mechanics

Solid-state Li-ion batteries have attracted tremendous attention in the past decade as a substitute for conventional liquid-electrolyte batteries. Inherently safer nature, prevention of Li dendrite formation, and significantly reduced active material dissolution are among the main advantages of using solid electrolytes (SE) in place of a liquid [1]. One of the drawbacks limiting the application of solid-state batteries is their propensity to crack due to non-uniform volumetric expansions across the SE/electrode interface. Such volumetric expansions result from lithium insertion and removal in battery electrodes [2].

Our objective in the present study is to evaluate the chemo-electromechanical response of electrodes and solid electrolytes in all-solid-state lithium-ion batteries. In particular, we measure *in situ* strain evolution in electrodes and the electrode/electrolyte interface vicinity using Digital Image Correlation (DIC). A previously-designed custom-cell [2] is modified to provide optical access to the working electrodes and solid electrolyte cross-section while the cell is charged/discharged. A garnet type solid electrolyte fabricated from $\text{Li}_{1.5}\text{Al}_{0.5}\text{Ge}_{1.5}(\text{PO}_4)_3$ (LAGP) investigated. Electrode surface measurements are conducted on a Au thin film working electrode coated on the LAGP SE via e-beam technique. Through-thickness measurements are performed on symmetric cells that use Li foil as both anode and cathode.

In both measurement scenarios, the custom-cell is assembled inside an Ar-filled glove box. The assembled custom-cell is mounted vertically in front of a 5 MP camera equipped with high magnification zoom lens to facilitate time-lapse acquisition of images from a sub-millimeter area of interest. Figure 1.1 shows the experimental setup developed in this study.

Results obtained from the Au electrode surface measurement indicate that mechanical strain generation initiates during the first lithiation cycle. Strain build up continues during the successive lithiation/delithiation cycles, giving rise to the formation of areas with highly localized deformations. SE through-thickness measurements also indicate highly localized strain regions

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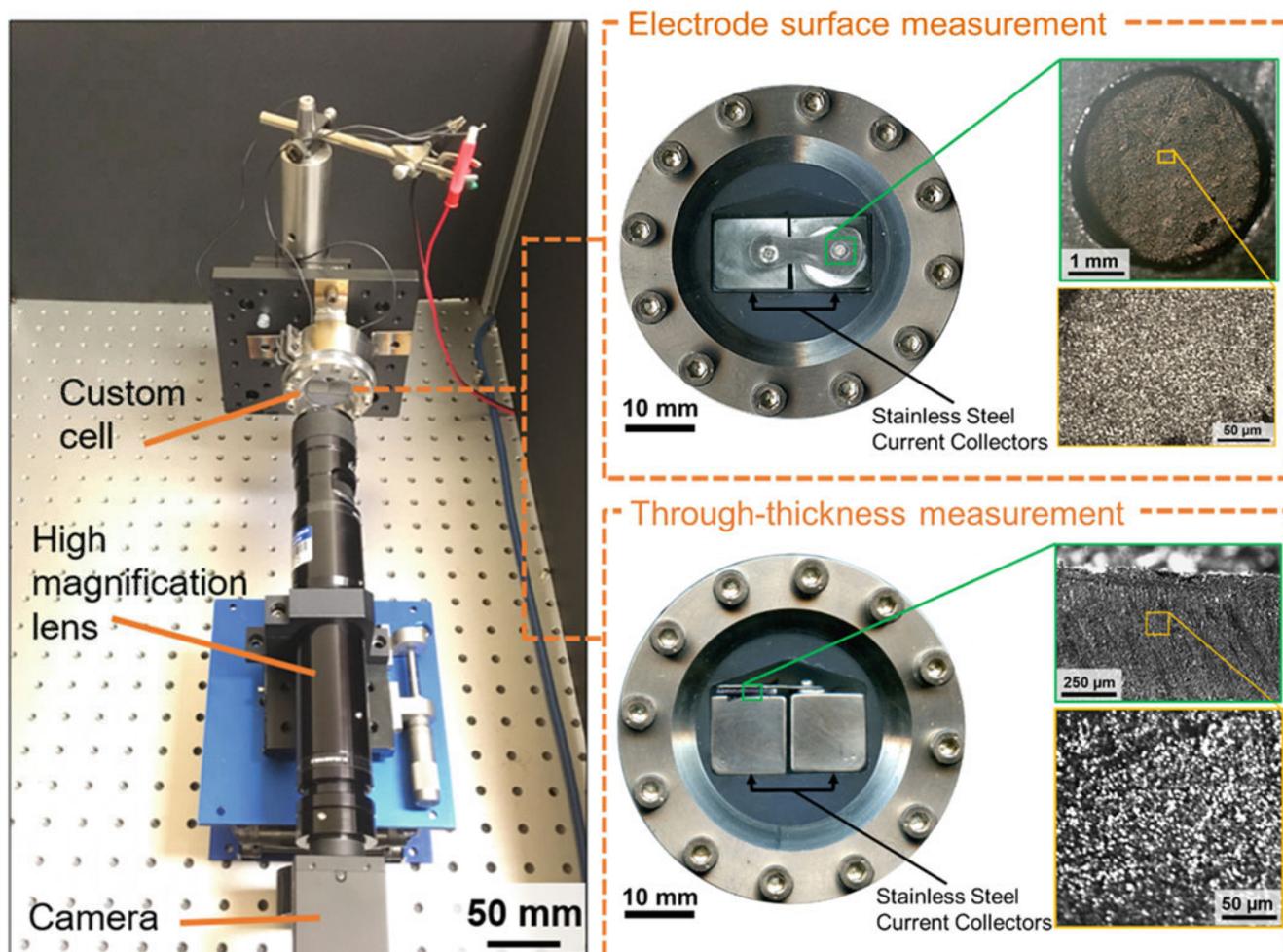


Fig. 1.1 Experimental setup used for *in situ* measurement of strains on working electrode surface and SE thickness

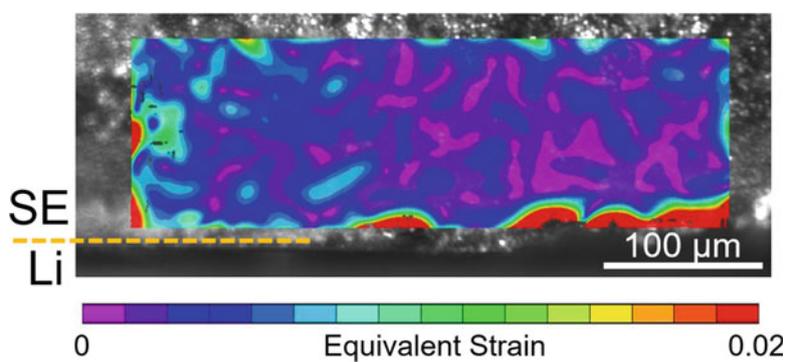


Fig. 1.2 Distribution of equivalent strain within a narrow region near the SE/electrode interface

near the SE/electrode interface. An example of such behavior is shown in Fig. 1.2. Ex-situ high magnification SEM images prove the presence of a narrow damage zone near the SE/electrode interface vicinity.

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Chapter 2

Crack-Tip Plastic Zone Size and Shape via DIC



G. L. G. Gonzáles, J. A. O. González, V. E. L. Paiva, and J. L. F. Freire

Abstract In this paper Digital Image Correlation (DIC) is used to characterize the crack-tip plastic zone size and shape under plane stress and plane strain situations. For that, two disk-shaped tension DC(T) specimens made of 1020 steel with thicknesses 2 and 30 mm were used in fatigue crack growth tests to simulated plane stress and plane strain conditions, respectively. Fatigue cracks were grown under quasi-constant ΔK (stress intensity factor range) and stress ratio (R) respectively equal to 20 MPa $\sqrt{\text{m}}$ and 0.1. A single 100% overload was applied when the crack reached a crack length of 6 mm (i.e. total crack length/specimen width = 0.3). Experimental measurements of the monotonic plastic zone at different stages during overload application are compared with finite elements simulations to predict the size and shape of the crack-tip plastic zone. A detailed discussion is given based on the DIC measurements obtained from the current investigation, including the experimental observations of crack closure.

Keywords Plastic zone · Crack closure · Fatigue crack · Digital Image Correlation

2.1 Introduction

During fatigue crack propagation, plastic deformation occurs ahead of the crack tip as a result of the high stresses that concentrate on its tip. The region affected by plasticity is known as the plastic zone. It is recognized that, for most metallic materials, the crack-tip plastic zone plays an important role because it is related to the mechanisms which govern the fatigue crack growth. Indeed, it can be stated that fatigue cracks do not grow by cutting virgin material. They always propagate through a region that has already been damaged by their prior load history [1]. According to Elber [2], plasticity-induced crack closure is associated with the residual plastic wake left behind the crack caused by the monotonic plastic zone ahead of a growing fatigue crack. Moreover, delay effects in fatigue crack propagation observed after overloading are related to the interaction of the plastic zone hypertrophied by the overload with the current plastic zone [3–5].

In the literature, most of the reported work utilizes approaches based on Linear Elastic Fracture Mechanics (LEFM) to characterize the crack-tip plastic zone size and shape. The crack tip models developed by Dugdale and Irwin are commonly used to estimate the plastic zone size for a crack under mode I loading. These models give a good estimate of the radius of the monotonic plastic zone size in front of the crack tip. A more accurate estimate of its shape can be obtained by using a yield criterion, Tresca or von Mises equivalent stress, in conjunction with the material yielding strength S_Y [6]. In this way, the elastoplastic border around the crack tip is estimated using only the linear elastic stresses generated by the mode I stress intensity factor K_I . Similar analyses can be made for crack opening modes II and III.

In this paper, Digital Image Correlation [7] technique has been used to experimentally characterize the shape and size of crack tip plastic zone. For that, the von Mises yield criterion has been employed to delimit the border of the plastic zone, indicating whether or not plastic yielding is to be expected.

Various researchers have also studied the crack tip plastic zone using DIC technique [8–11]. It is well known that the DIC technique provides accurate and reliable measurements of displacements and strains. This information is used to obtain important fracture parameters from the region surrounding the crack, such as crack open displacement (COD), J-integral, and stress intensity factor (SIF).

The objective of the current work is to characterize the plastic zone at the tip of a given crack during FCG test in conditions of plane stress and plane strain. For that, fatigue crack growth (FCG) tests were performed in specimens with thicknesses of 2 mm and 30 mm in order to simulate plane stress and plane strain conditions, respectively. It is known that the specimen

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