Mechanical Modeling of Battery Separator based on Microstructure Image Analysis and Stochastic Characterization

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Abstract

A microstructure-based modeling method is developed to predict the mechanical behaviors of lithium-ion battery separators. Existing battery separator modeling methods cannot capture the structural features on the microscale. To overcome this issue, we propose an image-based microstructure Representative Volume Element (RVE) modeling method, which facilitates the understanding of the separators' complex macro mechanical behaviors from the perspective of microstructural features. A generic image processing workflow is developed to identify different phases in the microscopic image. The processed RVE image supplies microstructural information to the Finite Element Analysis (FEA). Both mechanical behavior and microstructure evolution are obtained from the simulation. The evolution of microstructure features is quantified using the stochastic microstructure characterization methods. The proposed method successfully captures the anisotropic behavior of the separator under tensile test, and provides insights into the microstructure deformation, such as the growth of voids. We apply the proposed method to a commercially available separator as the demonstration. The analysis results are validated using experimental testing results that are reported in literature.

Keywords: Battery separator; Microstructure characterization; RVE; FEA; Mechanical properties

1. Introduction

Lithium-ion battery technology is widely used in electric vehicles due to its high energy density compared to other battery technologies. The mechanical behavior of the battery separator influences battery integrity when the battery is under external loads. To predict the battery response to mechanical loads and other abusive conditions, it is important to develop a method to accurately predict the mechanical behavior of the battery separator. Furthermore, quantifying the evolution of separator's microstructure during a deformation event is necessary to understand the underlying mechanism that could potentially lead to a thermal event induced by battery deformation. The microstructures of unloaded battery separators have been extensively studied using microscopic techniques. Arora and Zhang [1] have reviewed different types of battery separators, and provided the Scanning Electron Microscope (SEM) image of both the surface and cross-section of multiple separators. In the provided SEM images, the microstructure samples are large enough to be considered as Representative Volume Element (RVE). For heterogeneous microstructure, RVE is defined as a window [2-5] that contains a sufficient number of microstructure features, so that the property and microstructure statistics are spatially invariant when the bulk materials are sampled with such window size. In this work, the separator microstructure is characterized by descriptors such as the range of pore size, porosity and average tortuosity. Winkler [6] provided high-magnification microstructure images of battery separators, where the microstructures are characterized using average size of pore, carbon particle and silica particle. Even though 3D tomography has been employed to reconstruct a 3D microstructure of the battery electrodes [7], this method has not been applied to separator microstructure simulations. The effects of microstructure characteristics on separator's properties (e.g. mechanical, thermal and transport properties) have been studied experimentally [8-10]. Porosity and pore size distribution are used as the microstructural characteristics. To sum up, the aforementioned works focus on analyzing microscopic image of the separator, and represent its microstructure by some simple characteristics such as porosity, tortuosity, and pore size.

There are fewer works on microstructure-property modeling of the battery. Mechanical properties of the battery pack under various loading conditions have been studied using numerical modeling methods [11-13]. The RVEs defined in these works only capture the sandwich structure of the cell sheets (mesoscale), instead of the separators' micro features. Several works can be found on electrode microstructure modeling. The microstructure of the electrode has been modeled in 2D space to study the microstructural effects on the electrode properties [14]. However, the microstructure model is generated by randomly packing particles (represented by disks) into a 2D space, which is a simplification of the real microstructure. In another prior art, the microstructure of electrode is represented by a stack of tile-shaped "particles", where the reconstructed microstructure satisfies a pre-defined porosity and volume fraction of particles [15]. It is also a simplified representation of the real microstructure in numerical modeling. Liu and Mukherjee [16] have developed a Kinetic Monte Carlo-based algorithm to model the electrode microstructure. Nanoparticles of predefined shape (polyhedral, sphere and cuboid) undergo a simulated self-assembly process to formulate the microstructure. The interfacial area ratio is used to characterize the mixing quality of the electrode structure. The geometry of the nanoparticles is the same in one microstructure model, and the orientation of all polyhedral particles is fixed as a constant. This work focuses on the processing-microstructure simulation, instead of the microstructure-property analysis. None of the above works are targeted at the battery separator. The separator microstructure has not been studied in existing numerical modeling works.

We propose to predict the mechanical properties of the separator using microstructure-based finite element (FE) modeling. We also develop an image-based characterization method for quantifying the evolution of separator microstructure features during the simulated deformation process. To statistically represent the microstructure characteristics, there are three basic categories of microstructure characterization approaches: (1) the physical descriptor-based approach, (2) the N -point correlation function-based approach, and (3) the random field-based approach.

The first category is the physical descriptor-based approach. Key microstructure features are represented by physically meaningful parameters (descriptors). Typical microstructure descriptors fall into three categories: composition, dispersion status, and geometry. Composition descriptors indicate the percentage of each material constituent (e.g., volume fraction of filler). Dispersion descriptors describe the inclusions' spatial distribution status, such as the nearest neighbor distance, the ranked neighbor distances, pair correlation [17-21]. Geometry descriptors quantify the shapes such as the size/radius distribution, surface area, surface-to-volume fraction, roundness, eccentricity, elongation, rectangularity, tortuosity, aspect ratio, etc. [17, 21-27]. The major strength of physical descriptors is their clear physical meanings, so they can be easily mapped to processing parameters [28, 29]. With sufficient samples, the key descriptors of a certain type of materials can be determined using machine learning techniques [30]. *N*-point correlation function [22] is another category of widely used characterization/reconstruction techniques. Torquato et al. have shown that the microstructure of heterogeneous materials can be characterized statistically via various types of *N*-point correlation functions [18, 22-24]. With a good balance between computational cost and accuracy, 2-point correlation functions ($N = 2$) and 2-point cluster correlation functions [31] are widely used in practice. The correlation function is an infinite dimensional curve, causing difficulties for computational microstructure design optimization, and the function parameters lack a clear physical meaning. The third category is the Random field-based approaches. Microstructures are represented using a Gaussian random field [22, 32] or a Poisson random field [33]. The random field approach is featured by high computing efficiency, but it has a relatively low accuracy compared to the *N*-point correlation function-based methods. To study the evolution of the separator microstructure features when the separator is deformed, the physical descriptor-based approach is selected due to the clear physical meaning that it offers.

In this work, a new methodology is developed to study the separator's mechanical behavior based on its microstructure information (Figure 1). First, an image processing workflow is established to identify different phases from the microscopic image (Section 2). Then the processed image is transformed into a

pixel-mesh FEA microstructure model to simulate the stress-strain relation and the structure deformation of the separator (Section 3.1). During the deformation process, the microstructure characteristic is monitored and quantified using a descriptor-based microstructure characterization method (Section 3.2). The proposed method is tested by predicting the mechanical behavior of Celgard 2400 separator (Section 4). Conclusion and discussion are provided in Section 5.

Figure 1: Overview of the contents. The grey scale SEM image on the left is from [1].

2. Processing of microscopic image

A sample SEM image of the Celgard 2400's microstructure is shown in Figure 2. Three phases can be observed: large areas of lamellae, the thin fibrils and voids (pores). The large areas of lamellae are formed by the polypropylene (PP), whereas the fibrils are featured by much higher strength due to the aligned polymer chains, which is produced by the pulling and heating process of separator manufacturing. Therefore, the research question to be answered in this section is how to classify each pixel in the digital microscopic image into one of the three phases.

Figure 2: Image processing workflow to generate a 3-phase image for the separator's microstructure. In the output 3-phase image, voids (white), thin fibrils (red) and the large areas of lamellae (blue) are represented using different colors.

An image processing workflow is developed (Figure 2). This workflow includes four major steps:

(1) Input microstructure image. A square of side length l is cut from the SEM image of the battery separator. The size of the input square (sampling window) should be large enough to be an RVE, which contains a sufficient number of microstructure features. Microstructure samples obtained from the sampling window should be statistically equivalent in both microstructure features and material properties of interest. It is suggested to determine the minimum RVE size by trying a number of different window sizes, in order to achieve the balance between computational cost and prediction accuracy. The RVE microstructure image is smoothed by filtering out the high frequency noises. In the greyscale pixel image, the brightness is represented by the pixel value. 0 means black, and 255 means white.

(2) Identification of the voids. The shadow convolution function is employed to highlight the sharp changes in brightness (pixel values) between the polymer structure and the voids. After operating the shadow convolution, the values of the pixels of voids are reduced to 0 (black), and the pixels in the

polymer phase have positive values (different levels of greyscale). Binarization is conducted to distinguish the voids from the polymer: if the pixel value is equal to 0, this pixel is marked as void.

(3) Identification of the lamellae. By combining multiple low-pass filters, the image is blurred to the extent that the fine features such as thin fibrils are no longer identifiable. Approximately, the dark pixels in the blurred image represent the lamellae, and the light pixels represent the “porous” phase (fibrils and voids). A binarization step is required to distinguish the lamellae accurately.

If we plot the greyscale image in a 3D space (Figure 3), the bright part is correspondent to the “peaks”, and the dark part is correspondent to the “valleys”. The X and Y axes represent the image’s 2D dimension, and the Z axis represents the greyscale value. To binarize the image, a horizontal cutting level is determined. The part above the cutting level (Z threshold) is considered as the lamellae, and the part below the cutting level (Z threshold) is considered as the “porous” phase. The optimum Z threshold is determined using the algorithm presented in Figure 3. A series of different Z threshold values are tried to find the optimal value, such that:

- Minimize the total area of the “porous” phase;
- Contain the voids within the “porous” phase (minimize the overlap between the void region and the lamellae region).

(4) Identification of the fibrils. Before this step, we have already generated two binary images: one for voids, and the other one for lamellae. By overlaying these two images, the fibril pixels are identified as those that appear in the polymer phase of the void image, as well as in the “porous” phase of the lamellae image. In the void image, the polymer pixels excluding the fibril pixels are marked as the lamellae.

Figure 3: Optimized binarization for lamellae identification. g_l and g_u are the predefined lower and upper bounds of the Z threshold

3. Mechanical modeling and deformation analysis of the separator's microstructure

This section contains two tasks. First, an FE model is established to predict the stress-strain relation of the separator under tensile loading. Second, the deformed microstructures at different time steps of the virtual tensile testing process are recorded. Key microstructure features, such as the statistical distribution of the void size, long/short diameter and aspect ratio, are obtained using image-based microstructure.

3.1 Separator microstructure FE modeling and simulation

The 3-phase digital image exported from Section 2 is used to generate a mapped mesh (Figure 4a) of the microstructure. Each pixel is correspondent to one element in the mesh. The physical size of each element is obtained from the scale bar of the original SEM image. Different material properties are assigned to each phase. The input material properties can be obtained from experimental tests on pure material, or

from literature search. To obtain the stress-strain relation of the microstructure, a virtual tensile testing is simulated: the Degree-of-Freedom (DOF) on the Y direction is fixed at the bottom edge; the DOF on the X direction is fixed at the bottom left corner; an upward displacement is applied on the top edge of the microstructure. The displacement increases linearly with respect to the time. The X-displacement of the nodes on the left and right sides are constrained. The element type is shell element of thickness t . The lamellae elements and the fibril elements are assigned with different material properties.

The implicit solver in ABAQUS is employed to conduct the static analysis. The output of the simulation is the Y force of the nodes on the top edge. The stress is calculated as the total Y force divided by the top cross-section's area (t multiplies the side length l). The strain is calculated as the displacement divided by the original side length.

3.2 Image-based microstructure characterization

The image-based microstructure characterization method is employed to characterize the statistical information of the voids' morphology. Originally developed for quantifying the microstructure of polymer nanocomposites [34, 35], this descriptor-based characterization method is adapted for the voids' morphology in the battery separator. The characterization process is illustrated in the flowchart in Figure 4b. Three levels of microstructure features can be defined: *composition*, *dispersion*, and *geometry*. At the highest scale, *composition* descriptor captures the Volume Fraction (VF) of the voids. One level down, *dispersion* descriptors are capable to capture the spatial distribution of the voids, such as the distribution of the nearest neighbor distances of each void. On the lowest length scale, *geometry* descriptors capture the size and shape information of each void. It should be noted that descriptors used at each level are statistical, quantified by mean and higher order moments such as variance, skewness, etc. The descriptor values are firstly obtained in pixel, and then the pixel length is transferred to the physical length by multiplying the scale factor, which is measure from the scale bar of the original SEM image.

Figure 4: Microstructure FE model (a) and microstructure characterization process (b)

4. Simulation results and validation: Celgard 2400 separator

In this section, the microstructure of Celgard 2400 is modeled using the proposed method as a demonstration. Both the surface and the interior microstructures are shown in Figure 5. The interior microscopic image is generated by cutting through the sample using focused ion beam (FIB). Similar microstructure features can be observed in both surface and the interior microstructure images. In this work, the 2D microstructure features on the sample surface is used to represent the microstructure of Celgard 2400. It should be noted that the 2D microstructure model is only an approximation of the real 3D microstructure. A 3D microstructure reconstruction is needed for the most accurate material property prediction. Due to the length limit, this paper only focuses on the 2D microstructure model. The 3D microstructure reconstruction is left for the future work.

Figure 5: Microstructure features (surface and interior) of the Celgard 2400 separator

The simulated stress-strain curve is compared with the real material properties that are reported in literature. The evolution of the microstructure is also characterized using image analysis techniques. The image analysis-based microstructure characterization provides insights into the separator's behavior under abusive conditions.

4.1 Model setup and pre-simulation analysis

4.1.1 Model step: estimation of the input material properties

Ideally, the material properties of the lamellae and the fibril need to be obtained from experimental testing as the input of the microstructure simulation. Due to the small length scale of the microstructure features, Atomic Force Microscope (AFM) may be required to conduct the material property testing [36], which may incur a relatively higher experimental cost. In this work, we collect the material properties of the “base material” (polypropylene) from the literature. The Celgard 2400 is produced using ExxonMobil PP-4292 [37]. The stress-strain relation of this type of polypropylene [38] is considered as the property of the “base material”. The polypropylene is intruded during the manufacturing process of the separator. The

stress-strain relations of the stretched polymer phases are predicted by the strain hardening law and the strain in each phase.

The image analysis methods are employed to characterize the strains in the lamellae and the fibril for the prediction of the stress-strain relations (Figure 6). The geometric features of lamellae and fibril are produced by stretching the polypropylene sheet. It is assumed that round-shape microvoids pre-exist in the polypropylene before stretching. The microscopic image captures the deformed structure after the stretching process. The elongation (strain) of each material phase can be estimated as the aspect ratio of the voids inside it. For example, the elongation ratio ρ_f of fibrils is predicted as the aspect ratio of the voids adjacent to the fibrils. The elongation ratio ρ_l of lamellae is predicted as the aspect ratio of the small voids inside the lamellae. The aspect ratio of voids is defined as:

$$\rho = \frac{\text{Long diameter}}{\text{Short diameter}} \quad (1)$$

The average elongation ratio is equal to the average strain in the specified phase. After the strain of each phase is obtained, the strain hardening law is applied on the “base material” (polypropylene) to predict the stress-strain relations of the intruded materials (fibril and lamellae). Following the strain hardening law, the linear part of the stress-strain curve (elastic deformation) is shifted toward the right direction. The shifting distance is equal to the strain. The original yield strengths (A and A' in Figure 6) are replaced by the new yield strengths (B and B'). The elastic modulus of the lamellae, fibril and the “base material” are the same, but the fibril and lamellae have higher yield strength than the base polypropylene due to the stretching and unfolding of amorphous molecules.

4.1.2 Pre-simulation analysis: estimation of the structure porosity

Based on the prediction of stretch ratio, we can generate a rough estimation of the ratio between the thickness of the fibril and the thickness of the lamellae. Assuming that the volume of the material remains constant during the intrusion process, the ratio can be estimated as:

$$\delta = \frac{t_{fibril}}{t_{lamellae}} \approx \sqrt{\frac{\rho_l}{\rho_f}} \quad (2)$$

As mentioned above, ρ_f is the elongation ratio of the fibrils (the aspect ratio of the voids adjacent to the fibrils); ρ_l is the elongation ratio of lamellae (the aspect ratio of the small voids inside the lamellae).

According to the elongation ratios estimated from imaging analysis, we can estimate that $\delta = 0.6587$, which indicate that the fibril's thickness is 0.6587 times of the lamellae's thickness. Therefore, the bulk porosity ϵ of the microstructure is predicted as:

$$\epsilon = \epsilon_{void} + \epsilon_{fibril} \cdot (1 - \delta) \quad (3)$$

where ϵ_{void} is the area fraction of the voids; ϵ_{fibril} is the area fraction of the fibril phase. As the fibril is thinner than the lamellae (on the out-of-plane direction), the porosity contributed by the fibril phase is $\epsilon_{fibril} \cdot (1 - \delta)$. The porosity of our microstructure model is $\epsilon = 30.4\%$, which is confirmed by the reported 31~32% porosity in literature [39].

Similarly, we can compare the pore size information obtained from image analysis with the literature data. In literature, the pore size (diameter) is measured by intrusion and extrusion of mercury [39]. In our work, we use image analysis to measure the long diameter, the short diameter and the area of each pore. The equivalent diameter is calculated as:

$$D_{eq} = 2\sqrt{\frac{A}{\pi}} \quad (4)$$

The pore diameter reported in literature falls between the average long diameter and the average short diameter obtained from the image analysis. All the aforementioned comparisons are listed in Table 1.

Figure 6: Image analysis-based prediction of the lamellae and fibril's properties. The elongation ratio (strain) of each phase is predicted from the aspect ratio of the voids inside that phase. Strain hardening law is employed to predict the stress-strain curve of each phase after intrusion. The stress-strain curve of PP is from [38].

Table 1: Microstructure characteristics before deformation: comparison between the literature data and the image analysis results.

	Literature [39]	Image analysis
Porosity	31~32%	30.4%
Average pore size (experiment)	$\sim 0.05 \mu m$	
Average long diameter		$0.1335 \mu m$
Average short diameter		$0.0334 \mu m$
Average pore area		$0.0036 \mu m^2$
Average equivalent diameter		$0.0612 \mu m$

4.2 Simulation of the stress-strain relation

Two simulations are conducted: virtual tensile test on machine direction (MD), and virtual tensile test on transverse direction (TD). The simulated stress-strain curves and the experimental testing results [40] are plotted in Figure 7a. The proposed modeling method captures the anisotropic behavior of the battery separator successfully. For the same strain level, stress along MD is larger than the stress along TD. Such anisotropic behavior can be explained by the deformation pattern of the microstructure. When the microstructure is intruded in the MD direction, the thin fibrils play the role of loading path in the deformation process. The voids are stretched along their long axis. On the other hand, the voids become wide open when the microstructure is intruded along the TD direction. Very few stresses are distributed on the fibrils, indicating that only the soft lamellae serve as the loading path.

However, some discrepancies exist between the simulation and the experiments when the strain is large. There are three major causes of the prediction error:

- (1) The input stress-strain curves of each phase are estimated based the literature information, with the assumption of isotropic properties. The anisotropic behaviors of the RVE are primarily induced by the effects of microstructure. Compared to the experiments, the simulated MD stress is lower, and the simulated TD stress is higher, because the inherent anisotropy of the material is not considered. The simulation accuracy can be improved if the real anisotropic properties of each phase are used.
- (2) The size of the microstructure sample may not be as large as an RVE. When the size of microstructure sample is increased, the simulated microstructure properties will converge to the macro properties that are observed from tensile bar testing.
- (3) 2D representation of a 3D microstructure always introduces errors due to the lack of microstructure information on the in-depth direction. The prediction accuracy can be improved by obtaining the real lamellae and fibril properties from experimental testing, and by using a large window size in 3D microstructure imaging and digital reconstruction.

4.3 Microstructure evolution study

In addition to the stress-strain prediction, the evolution of microstructure statistics can be obtained via image analysis from the deformed microstructure (Figure 7c). In the image analysis process, the geometry of each void is firstly extracted from the deformed microstructure. The coordinate of the void is also obtained as the spatial location information. The second step is to determine the void's major and minor axis, by which the long diameter (parallel to the major axis) and the short diameter (perpendicular to the major axis) are calculated. Aspect ratio of the void can be calculated as the ratio of the long diameter over the short diameter. Furthermore, the area of each void is obtained by counting the number of pixels contained in that void.

When loading in the MD direction, a larger deformation will lead to a larger long diameter, because the void is stretched along its major axis. The short diameter will decrease due to the contraction of the microstructure on the unloaded UD direction. When loading in the TD direction, the increasing in long diameter is not apparent. However, the short diameter and the pore area increase significantly under the TD loading due to the opening of the void.

Another interesting study is to compare the distribution of void diameter with the size distribution of electrode particles. For example, when the microstructure is stretched to 30% strain, the longest diameter is around 470 nm, which is smaller than the minimum diameter of the $\text{LiNi}_{1/3}\text{Mn}_{1/3}\text{Co}_{1/3}\text{O}_2$ particles (approximately 700 nm) [41].

Figure 7: Results of simulation and microstructure characterization. (a) Comparison of simulated stress-strain curve and the experimental testing results [40]. The experiment is conducted on Celgard 2400 in the dry condition. The testing is done using a DMA with a submersion film/fiber clamp. The loading rate is 1N min^{-1} ; (b) The deformed shapes; (c) The evolution of the long and short diameter of the pores during the deformation process

4.4 Impact of the microstructure images' resolution

As the FE model is built on a pixelated structure, there is no “smooth” boundary in the model. The curved boundary is discretized into a spatial arrangement of square elements/pixels. For example, a circle is rasterized (approximated) by a circular configuration of square elements (Figure 8). An interesting research question arises from such approximations: whether the pixelated model is accurate enough to represent the real structure of a smooth boundary. The stress concentration in the pixelated model might have a strong impact on the prediction of the RVE properties.

To answer this question, a comparative study is conducted on images of different resolutions (Figure 8). For the same Statistical Volume Element (SVE) microstructure sample, four meshes are generated with different resolutions. The resolutions of the four meshes are $\times 3$, $\times 2$, $\times 1$ and $\times 0.5$ times of the original resolution. The physical size of the four meshes are the same (as they are representing the same structure), but the number of elements are different. For example, there are 100×100 elements in the $\times 0.5$ resolution mesh, and 600×600 elements in the $\times 3$ resolution mesh. In the image of the lowest resolution ($\times 0.5$), the boundary of the void is rough and inaccurate because it is represented with a limited number of pixels. The sharp corners on the pixelated void boundary will induce severe stress concentration. By contrast, the void boundary is much smoother in the image of the highest resolution ($\times 3$). If the resolution of the image is increased to $+\infty$, the pixelated boundary becomes a smooth boundary.

With the same setup of the loading step and the boundary condition, the properties (stress-strain relation) of the four meshes are simulated and plotted in Figure 8. The mesh of the original resolution has almost the same stress-strain curve as the high resolution mesh ($\times 3$). Increasing the resolution from $\times 1$ (original) to $\times 3$ will not change the simulation result significantly, while a huge prediction error is observed in the simulation of the lowest resolution ($\times 0.5$). The conclusion from this convergence study is that the original resolution is preferable due to the low prediction error, and the low computational cost (less number of elements). Further increasing the resolution to make the structure smoother will not change the simulation results significantly. However, reduction in the resolution will incur the danger of losing the prediction accuracy.

Figure 8: Comparison of the simulated material properties with different levels of image resolution

5. Conclusion and future works

In this paper, an image-based microstructure characterization and modeling method is developed to analyze the stress-strain property of the battery separator. An image processing method is developed to distinguish three phases from the microscopic image: polymer lamellae, polymer fibril, and voids. A FE mesh is generated based on the processed image of the separator's microstructure RVE. The material property of each phase in the microstructure is estimated based on the literature information. FE simulations are conducted to obtain the stress-strain relation of the battery separator. The simulations are validated by the experimental testing results reported in the literature. Furthermore, image-based microstructure characterization is conducted to obtain the statistics of the voids in the deformed microstructure. Compared to the existing works, our research has made following major contributions:

(1) A novel image analysis method has been developed. Different material phases are identified from the microscopic image of the battery separator. Microstructure features are quantified statistically.

Furthermore, the method enables the establishment of FE mesh of the microstructure.

(2) A microstructure modeling method has been developed. This method captures the anisotropic properties of the battery separator successfully.

(3) The statistics of the deformed separator microstructure is obtained using the image-based microstructure characterization methods. This information will be critical for understanding the root cause of battery thermal runaway.

The limitations of this work are summarized as the future works. First, it is necessary to study a variety of loading conditions such as compressing, bending, or tensile under different strain rates. A comprehensive study of microstructure behavior under various loading conditions is critical to understand the failure mechanism of battery under external loads (e.g. vehicle crash). Second, the current study doesn't consider the failure of the material (polymer fracture). The next step is to add the failure criteria of polymer into the existing model, which will enable us to study the microstructure behaviors under extreme loading conditions. Third, a 3D microstructure reconstruction is needed to capture the complex microstructure features such as the tortuosity of pores in the 3D space. Forth, the proposed model needs to be extended to a wide range of temperatures. The input material properties of the microstructure model will be the stress-strain-temperature relation of polypropylene (e.g. the family of stress-strain curves under different temperatures). In particular, the battery separator's behaviors in the real working temperature will be investigated.

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