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Deformation and failure characteristics of four types of lithium-ion battery separators

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HIGHLIGHTS

- Mechanical properties and failure mechanisms of four commercial separators measured.
- Wet processed ceramic coated separator shows highest strength.
- Area of short-circuit changes based on separator type used.
- Effective finite element model of PE separator was developed.

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ABSTRACT

Mechanical properties and failure mechanisms of battery separators play a crucial role in integrity of Lithium-ion batteries during an electric vehicle crash event. In this study, four types of commonly used battery separators are characterized and their mechanical performance, strength, and failure are compared. This includes two dry-processed polyethylene (PE) and trilayer separators, a wet-processed ceramic-coated separator, and a nonwoven separator. In detail, uniaxial tensile tests were performed along machine direction (MD), transverse direction (TD) and diagonal direction (DD). Also, through-thickness compression tests and biaxial punch tests were conducted. Comprehensive mechanical tests revealed interesting deformation and failure patterns under extreme mechanical loads. Last, a finite element model of PE separator was developed in LSDYNA based on the uniaxial tensile and through-thickness compression test data. The model succeeded in predicting the response of PE separator under punch tests with different sizes of punch head.

1. Introduction

To reduce risk of mechanical and thermal failure of battery cells, Electric Vehicle (EV) battery packs are protected by strong casings outside of the crumple zone. The mechanical and thermal behaviors of the EV lithium-ion batteries under crash loading are still not fully understood. Researchers are continuously working on testing and modeling of the mechanical properties of lithium-ion battery cells and their components [1–9]. One of the most important components of the battery interior is its separator. It is the failure of a separator that causes contact between anode and cathode or their current collectors and lead to internal short circuit.

Most common type of separators are polymeric porous membranes, made of polyolefin, such as polyethylene (PE), polypropylene (PP) or their combination [10]. To improve the thermal performances of the battery, ceramic-coated PE or PP and nonwoven separators have emerged. The manufacturing processes, to be specific, dry and wet processes, bring significant effects on separator's mechanical properties. The dry processed one is highly anisotropic in machine direction and transverse direction.

A better understanding of the mechanical behavior of the separators helps to rank the properties of different types of separators under mechanical abuse loading and choose the one satisfying specific requirements of the battery pack. There are only few test standards, such as American Society for Testing and Materials (ASTM) D882 for tensile test of thin plastic sheets and ASTM D1306, D3763 for low and high rates puncture tests of separators [11]. However, those standards were designed to characterize nonporous thin films, while separators properties are highly affected by

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their porosity and manufacturing method. For example, the difference in properties in machine direction versus transverse/diagonal and through thickness directions would not be realized by standard testing. Also, practical tests representing real world accidents such as punch loading with various hemispherical punch sizes are missing from all current standards.

In an earlier study, current authors characterized properties of two typical dry processed battery separators of PE and tri-layer (PP/PE/PP) types [12]. Most of other studies on strength of separators have also concentrated on these types of separators [7,13–16]. However, the ceramic-coated wet processed and ceramic nonwoven separators are the more advanced and promising types, which have not been adequately studied. Not only their deformation mechanism in all loading directions should be well characterized, also their failure mechanism and the differences with more conventional dry-processed separators should be understood.

In this research, two commercially available commonly used separators, wet processed ceramic-coated and ceramic nonwoven, were studied and their properties were compared to dry processed PE and trilayer separators. The separators were purchased from MTI Corp, with thicknesses ranging from 16 to 31 μm, see Table 1. One of the objectives was to provide detailed comparison of mechanical strength and failure of these separators in all probable loading conditions. Uniaxial tensile specimens were cut with a range of specimen width from 5 to 25 mm to study the effect of tensile specimen geometry on failure properties. Also a range of punch sizes from 1/8 inch (3.175 mm) to 1 inch (25.4 mm) were used for biaxial tests. In the last section of the paper a finite element modeling approach was developed for PE separators. Promising results were obtained when compared against tests.

2. Experimental methods and results

2.1. Tensile tests

Specimens were prepared according to ASTM standard D882 for thin films, having a strip shape with a uniform width. Since there are no special specifications for the width of strip separator, specimens were cut at five different widths: 5 mm, 10 mm, 15 mm, 20 mm and 25 mm, to study effects of specimen width on deformation and fracture strain. The strip specimen length was fixed as 60 mm and the gauge length was chosen as 35 mm. A sharp razor was used to cut specimens along machine direction (MD), transverse direction (TD) and two diagonal directions (+DD and -DD), as shown in Fig. 1a, while the separator was sandwiched between 5-mm Cartesian graph paper, to have enhanced precision for the width and improve quality of cut. An Instron 5944 uniaxial tensile machine with 100 N load cell and a constant 25 mm/min speed was used to perform the tests. Digital image correlation (DIC) method (Vic 2D, 2009) was used to calculate the strains. Fig. 1b shows test results for all types of separators studied, in four directions. For dry processed PE and trilyer separators, the response is highly anisotropic. The strength in MD (>120 MPa) is much larger than that in DD and TD (<20 MPa). The strengths in −DD and +DD are identical. The wet processed ceramic-coated one has comparable stress levels in four directions (>140 MPa), though the initial elastic moduli are different. The nonwoven separator has much lower strength (<35 MPa), which is similar in TD and MD, while it is weaker along DD, mainly due to the orientation of fibers. Its failure stress and strain levels are approximately five times smaller than the polymeric separators. It is worth pointing out that the stress-strain curves along + DD and −DD are different for ceramic-coated and nonwoven separators.

The fracture strains for specimens with different widths in each direction are compared in Fig. 2a (+DD and −DD are combined as DD here). The standard error bar shows a large spread of the fracture stain with different widths. From these tests, we have found that: a) fracture strains of all the four separators in DD have relatively large variations; b) Compared to the other three, wet processed ceramic-coated separator has smaller variation of failure strain; c) the smaller the width of specimens are, the larger the variation due to cutting defects.

For dry processed separators, the failure modes are quite different in MD, TD and DD, as shown in Fig. 2b. The failure during MD loading of these two separators created zig-zag failure surfaces perpendicular to MD while failure surface in TD loading is much smoother. Stretch-induced wrinkling perpendicular to loading direction was observed for the TD and DD tensile tests of PE and trilayer specimens. The wrinkles and folds are believed to be due to clamped boundary conditions and only happens at certain range of tensile strains [17]. DD loading is characterized by large shear zones and extreme fracture strains. In large strains, the deformed regions of specimens in TD and DD became transparent (the undeformed separator was solid white). The differences in failure modes of dry processed separator in two directions is extensively discussed in Ref. [12]. For the ceramic coated separators, deformed shapes are similar in all three directions, characterized by a smooth necking area in the center of specimen. The nonwoven samples have minimal change of shape during loading as they fracture in relatively small strains (ε_f<0.12).

From the above observations, in order to characterize a new separator type it is recommended to cut strips at four directions (MD, TD, +DD and -DD). In terms of width of the specimen, more reliable data is obtained when the width is 10 mm or more.

2.2. Compression tests

For the compression tests, 40 layers of round (16 mm diameter) specimens were stacked together and were compressed using a 200 kN MTS loading frame. A pre-compression of 0.5 MPa (following [15]) was used to make sure there were no gaps between the layers. Tests were repeated five times for each type of separator. The loading was applied until a 100 MPa stress and was followed by unloading to zero stress.

The nominal stress-strain curves and shapes of deformed round specimens are shown in Fig. 3. While dry processed PE (Fig. 3) and trilayer separators deform to an oval shape with major axis along MD (as also reported by Ref. [12]), the ceramic-coated (Fig. 3) and nonwoven separators, remained round after the tests. This is mainly due to the high in-plane anisotropy of the dry processed

Table 1
Separator specifications.

	1	2	3	4
Material	PE	PP/PE/PP	Alumina/PE/Alumina	Nonwoven
Process	Dry	Dry	Wet	Wet-laid [11]
Thickness (μm)	25	25	16 (2/12/2)	31
Porosity	36%–46%	39%	37%	46%
Pore size (μm)	0.01–0.1	0.05 × 0.21	0.1 (average)	0.2 (average on mat surface)