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Effect of State-of-Charge and Air Exposure on Tensile Mechanical Properties of Lithium-Ion Battery Electrodes

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The large deformation and failure behaviors of electrodes under various SOC conditions are essential for understanding the battery impact response and reconstructing battery impact scenarios with numerical methods. Depending on the chemical activity, the electrodes may react with oxygen if exposed to air, which leads to change of mechanical properties to some extent. To obtain the real mechanical properties of electrodes as they are sealed inside a battery, an argon-protected testing method was developed to test the electrodes. In this way, we identified the SOC sensitivities of tensile behaviors for the electrodes extracted from a pouch cell for electronic devices. The mechanical properties of anode change with SOC but the cathode does not present apparent difference. By comparing test results of anode and anode current collector under different SOCs, we inferred that anode current collector is responsible for the SOC effect of anode. We further evaluated the influence of oxidation on the tensile behaviors of electrodes at different SOCs after exposing them in the air for different durations. For anodes from charged batteries, we combined with a couple of competing mechanisms to explain the non-monotonic change of mechanical properties along with air exposure.

At the macro-scale level, Xu et al.2 reported evident SOC dependence of the mechanical response in indentation tests of a 18650 cylindrical cell. They found that the increase of SOC enhances the battery mechanical response and makes failure occur earlier. Li et al.3 confirmed a similar phenomenon in cylindrical cells and on the other hand demonstrated that the SOC sensitivity of mechanical response of pouch cells is much weaker. Researchers inferred that the major mechanism incurring the different SOC dependencies between cylindrical cells and pouch cells is the internal stress built during charging of the batteries.4,5

Besides the internal stress mechanism, we still need to get a correct understanding of the variations in mechanical properties of the battery constituents due to the change of SOC and how much they contribute to the different macroscopic behaviors of different cell types. These demand proper design of mechanical experiments for constituent materials. In general, the jellyroll of Li-ion batteries is a multi-layered structure composed of thin layers of electrodes (cathodes and anodes) and separators. Since the strength of electrodes is much higher than that of separators, and the electrodes take up a much larger proportion in the volume of jellyroll, their mechanical properties play a more important role in the battery response under crushing.6 Many tests and simulations have been conducted on battery electrodes to acquire their mechanical properties.7–14 For example, Bonatti et al.11 and Pan et al.12 characterized the tensile behavior of current collectors in electrodes focusing on anisotropic elasto-plasticity and strain-rate dependence. Zhu et al.13 tested the granular active coating materials in electrodes and employed the Drucker-Prager Cap model to characterize them. It has to be pointed out that most of the tests were performed with the electrodes extracted from batteries fully discharged. Therefore, the SOC effect on the mechanical properties of electrodes has not been fully considered so far. Xu et al.9 attempted to study the SOC dependence of electrodes and reported that the anode became stronger and more brittle with increase of SOC, but their experiments did not exclude the possible influence of environment on the chemically active materials, especially for those from the charged batteries.

At the micro-scale level, chemical reactions take place inside a battery during the charging-discharging process, the Li-ions are exchanged between cathodes and anodes. Li-intercalation and deintercalation lead to the change of the electrodes in terms of chemical configurations and possibly, the mechanical properties in the meantime. Some previous researchers have conducted analyses on variations of mechanical properties of active particles due to change of SOC.15–23 For cathodes, Swallow et al.20 measured the change of Young’s modulus and hardness for LCO particles via nano-indentation tests. Vasconcelos et al.21 considered the influence of electrolyte on the cathode particles with the similar approach, and Mao et al.22 observed the charging-induced strain, heterogeneity and micro-cracks in cathode particles with a synchrotron-based X-ray diffraction (XRD) method. For anodes, Qi et al.23 indicated a threefold increase in Young’s modulus of graphite particles via simulations based on the Density Functional Theory, and Mukhopadhyay et al.16 studied the thin-film graphite experimentally and reported the stress generation during Li-intercalation. For the purpose of interpreting mechanisms, core–shell models are widely used to represent the active particles. For example, Wu and Lu24 used the core–shell model to study the diffusion stress, Zhao et al.25 employed it to explain the fracture and de-bonding of active particles, while Suo et al.26 studied the insertion-induced cracking in LiFePO4 particles based on fracture mechanics.

The micro-scale investigations mainly focused on active particles and did not touch the stage of large deformation that the mechanical abuse cases concern much more. Although they proved that SOC significantly affects the performance of active materials in electrodes, the strength increase reported in those studies is much larger.

Nowadays the manufacturers of electrical vehicles compete in increasing the amount and the energy density of Li-ion batteries to increase vehicle mileage. Accompanying this, safety issues of the Li-ion batteries in application draw much attention and are worth discussing in depth, especially when an electrical vehicle encounters a collision. Mechanical abuse loadings could lead to failure of the battery constituents (cathodes, anodes, and separators) and cause internal short-circuit. If heat is intensively accumulated during severe internal short-circuit, thermal runaway would take place, even resulting in fire and explosion. Previous studies have demonstrated that the thermal runaway risk of Li-ion batteries positively correlates with state-of-charge (SOC).1 Understanding the mechanical properties of the battery constituents under realistic work conditions (e.g. at various SOCs) is one of the keys in the battery safety research. However, how SOC affects mechanical behaviors of Li-ion batteries as well as the constituents has not been thoroughly clarified.

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than the macroscopic experimental results at the cell level. To achieve a better explanation of the macro-scale phenomena, more elaborated tests of the electrodes are required and the SOC effect should be clarified by carefully considering the realistic environmental condition. The purpose of the present study is to address the SOC dependence of the large-deformation mechanical behavior of the electrodes with experiments considering the environmental influence. Since the electrodes at higher SOC that have strong chemical activity can quickly react with oxygen in the air, an Argon-protected mechanical testing method is developed and used to acquire the electrode behavior without influence of air exposure. The contributions of active coating and current collector in the SOC effect are distinguished. Meanwhile, the oxidation influence on the electrodes is also studied and quantified with a series of comparative tests. Finally, scanning electron microscope (SEM) observation is performed to identify the micro-scale morphologic change at different SOCs and further support the experimental findings.

**Experimental Preparation**

*Pouch cell for extracting electrodes.*—The tested electrode materials were extracted from a Li-ion pouch cell with a lithium cobaltate (LCO) cathode and a graphite anode, the dimensions of which are shown in Fig. 1a. The cathode is an aluminum foil double-sided coated with LCO active materials. The thickness of the aluminum foil is 10 μm, and the LCO active layer is about 58 μm. Likewise, the anode is composed of a copper foil of 8 μm thickness and graphite material coating of 65 μm. The electrodes take most of the volume of the battery (over 80%) and their tensile mechanical properties are important to batteries when they are subjected to bending or punching loadings. The specimens were cut in 3 directions from the electrodes, as shown in Fig. 1b, with which tensile tests were conducted. For the convenience of describing anisotropy, the battery rolling direction is defined as 0° direction, and the other 2 directions are defined as the angle relative to the rolling direction (45° and 90°).

As the major factor concerned in the present study, SOC of the battery should be accurately calibrated and controlled based on the voltage-SOC relationship plotted in Fig. 1c. By monitoring the battery voltage and the input charge quantities, the fully charged battery was discharged from 4.4 V with a constant current of 0.1C. It suspended at every 5% SOC for 30 min until the voltage rise diminishes apparently. Then the discharging continued and the above operation repeated until the battery reached the target SOC. Batteries at 4 SOCs (0%, 30%, 60% and 100%) were prepared in this way for studying the SOC effect on the mechanical properties of electrodes.

**Argon protected sample preparation and testing procedures.**—In the present study, all the dismantling operations of batteries were conducted inside an argon-filled glovebox, as shown in Fig. 2a. This ensures that the batteries, especially of high SOC, are isolated from air when dismantled, so as to prevent intensive redox reactions. Furthermore, we kept the argon protection for the samples of electrodes when they were moved from the glovebox and subjected to mechanical testing. This is to avoid the air oxidation of charged electrodes due to their high chemical activity. Oxidation may lead to quite different mechanical behaviors of electrodes, which will be clarified in the next sections.

Figure 2b shows the different appearances of the anode from the battery of 60% SOC with and without argon protection. The active layer surface of the anode under argon protection appears in brown. Once the anode is exposed to air, the surface color turns to black in seconds, together with a great amount of heat generated. Figure 2c exhibits the argon protected anodes under different SOCs (0%, 30%, 60% and 100%). It can be seen that argon protection well maintains the real feature of anode inside battery. With increase of SOC, the surface color of anode changes from dark black to bright yellow. It reflects that more Li-ions accumulated in the graphite materials, which is also reported by other researchers.

Electrode specimens of dog-bone shape were prepared in the argon-filled glovebox, with a die-cutting mold as shown in Fig. 3a. The specimens of all three material directions have the same dimensions, which are designed to accommodate the width of battery cell.

A convenient method was developed to isolate the specimen from air in performing the mechanical test of the electrode, which is

![Figure 1](image-url).

**Figure 1.** Description of test samples: (a) pouch cell for testing, (b) definition of material directions for electrodes, and (c) voltage vs SOC of the pouch cell.
described as follows. (1) After dismantling the battery cell and extracting the electrode sheets in the argon-filled glovebox, the electrode specimens are cut along three different angles with the die-cutting mold. (2) Each specimen is sealed into a ziplock plastic bag which is longer than the specimen, as shown in Fig. 3b, and all the bags are taken out from the glovebox. (3) On the universal testing machine, the specimen is clamped at the two grip sections together with the two end parts of the surrounding bag, which makes sure that the middle part of the bag has a redundant space to allow separately stretching the electrode specimen in the tensile test, as shown in Fig. 3b. (4) After a slight pre-straining, the tensile test of the electrode specimen with argon protection is performed using the testing machine and the force vs displacement data are acquired.
We took two approaches to verify the feasibility of the argon protected test. Firstly, we laid up a sealed anode specimen of 100% SOC for a week after the tensile test. It can be observed that, after such a long time, the sealed specimen kept the same bright yellow surface as the primary state, as shown in Fig. 3c. This indicates that the seal with the ziplock bag can well prevent the anode from being oxidized by air. The other concern is whether the ziplock bag affects the force measurement during the tensile test or not. Two cathode specimens in the same status were tested within and without the ziplock bag sealing. As the property of cathode is not influenced by air even at high SOC, as shown in section Experimental Results—Air exposure effect on tensile behavior of electrodes, the two specimens should have the same mechanical response, which was well validated with the test results in Fig. 3d.

Experimental Results

Tensile behavior of argon protected electrodes.—All the tensile tests of the electrode specimens in the present paper were performed more than 6 times on a Zwick 2020TE testing machine with a loading speed of 0.01 mm s⁻¹, referring to the strain-rate of 1 × 10⁻⁴ s⁻¹. The stress-strain curves of electrode materials under the argon protection are shown in Fig. 4. The SOC dependencies of the argon protected electrodes are shown in Fig. 4a. Since the metal foil (i.e. the current collector) has higher strength than the active layers, the cathode and anode act like aluminum foil and copper foil with a typical elastoplastic behavior. For the cathode, SOC does not make much difference in the mechanical properties. The stress-strain curves at the four SOC levels are almost superposed, and all the failure strains are around 0.011. However, for the anode, SOC has a quite significant influence. The failure strain of anode decreases with SOC, which reduces from 0.014 for 0% SOC to 0.007 for 100% SOC. The stress-strain curve exhibits a non-monotonous change: the ultimate strength keeps increasing from 0%, 30% to 60% SOC, but when SOC comes to 100%, the curve returns to the same trajectory as the one of 0% SOC and the ultimate strength becomes the lowest.

We also examined the anisotropy of the electrode materials via tensile tests along three different orientations (Fig. 4b) to make sure that the predominant factor in Fig. 4a is SOC. It can be seen that for cathode, although the flow stress along 90° degree (transverse direction, TD) is slightly higher than the other two, the anisotropy of the cathode is actually negligible. The same conclusion also applies to the anode.

Based on the electrochemical fact that the lithium ions transfer from cathode to anode with an increase of SOC during charging of battery, a natural speculation would be that the cathode becomes strengthened and the anode becomes weakened. In other words, according to the test results above, the anode presents a relatively complicated non-monotonic change of the tensile response, while the cathode behaves almost with no change. Further analysis indicates that the change of anode tensile properties with SOC in an inert gas mainly attributes to the copper foil current collector, which will be described below.

Air exposure effect on tensile behavior of electrodes.—The tests above retrieved the electrode properties by mimicking the oxygen-free environment inside the battery at different SOCs. In contrast, many researchers in the literature conducted the electrode mechanical tests in the air, and different conclusions related to SOC effect were drawn. Oxidation could be a factor that led to a big difference. In this section, we carried out a series of tests especially to examine the influence of air exposure on mechanical behavior of electrodes at different SOCs.

All the specimens were extracted and sealed within ziplock bag in the glovebox. To realize a certain degree of oxidation, a specimen was taken out from the bag, exposed to air for a fixed duration, and then subjected to a tensile test. The specimens of all the four SOCs were tested with air exposure durations of 0, 5, 10, 30, 60 and 180 min, respectively. Note that for anode, additional exposure of 24 h was included (regarded as sufficient exposure in the present paper). For each exposure duration and each SOC, at least 6 specimens along 0° direction were tested to ensure the credibility.

Figure 5a exhibits the test results of cathode with different oxidation durations. It shows that the tensile behavior of the cathode does not change with the exposure duration. In other words, neither oxygen nor water vapor in the air has significant effect on the cathode at any SOC. The major reason could be that the cathode active layer of lithium salt oxide does not tend to react with air constituents.

As for the anode, the test results in Fig. 5b show that the anode has a significant dependency on the exposure duration. At 0% SOC, both Young’s modulus and plastic flow stress level decreases with the increase of the exposure duration. After sufficient exposure (24 h), the ultimate strength of anode becomes 16 MPa, about 73% of that of the unexposed anode (22 MPa). This phenomenon shows that even the anode of 0% SOC is also affected by air exposure. In other words, if the 0% SOC anode is tested without air isolation, the mechanical properties could be underestimated depending on exposure time. In addition, it can be seen that the exposure increases the failure strain of the 0% SOC anode.

For the 30% SOC anode, the influence of air exposure becomes complicated. It can be seen that the stress keeps increasing until exposure time of 10 min, while the strength turns to decrease from 10 min to 180 min. The ultimate strength of the anode after 180 min exposure becomes even slightly smaller than that of the unexposed anode. Based on this non-monotonic trend, the air exposure effect can be divided into two stages: short-time strengthening and long-time weakening. Another interesting phenomenon is observed in terms of the 30% SOC anode after sufficient exposure: The stress-strain curve exhibits an apparent turning point around the strain of 0.005, and then enters a plateau stage until the final failure. Thereby it loses the similarity to metal foil materials in terms of elastoplastic behavior, quite different from the 0% SOC anode after sufficient exposure.

At 60% SOC, the non-monotonic air exposure effect is also exhibited, but the short-time strengthening effect extends to 60 min exposure when the ultimate strength comes to 38 MPa, about 52% larger than that of the unexposed anode. The strengthening effect looks more dominant at this relatively high SOC: The stress-strain curve of 180 min exposure, and the early stage of the curve after sufficient exposure (24 h) as well, just show a slight trend of weakening. The stress-strain curve after sufficient exposure also has the turning point (around the strain of 0.003) and the plateau stage. Besides, a sudden drop of stress occurs at the beginning of the plateau stage, and a tendency of stress rise is observed at the end of the plateau stage. We infer that such a drop is attributed to some damage initiation, but no apparent crack appears on the specimen surface at that moment.

At 100% SOC the fully charged state, the anode specimens that suffered air exposure all exhibit the stress-strain behavior with a turning point (around the strain of 0.004) and a stress plateau, and the stress rise at the end of the plateau becomes more significant. No crack appears on the specimen surface during the entire deformation before the final failure, but the three-stage feature of stress-strain curve implies a damage mechanism in the tension process of the 100% SOC anode after air exposure. Particularly, stress drop also occurs in the plateau stage of the 100% SOC anode after 24 h exposure, quite similar to the 60% SOC anode. On the other hand, the non-monotonic change of the 100% SOC anode tensile behavior along with exposure duration, i.e. short-time strengthening and long-time weakening, can still be clearly identified when we observe the early deformation stages before the turning point of all the stress-strain curves.

Contribution of anode current collector.—It is difficult to explain the SOC effect and air exposure effect on the anode mechanical behavior only with the experimental observations on the entire anodes since the anode is a sandwich-like structure
consisting of a layer of the current collector and two layers of active coating. To identify the dominant factors and underlying mechanisms, additional tests and analyses are required. In this section, we performed tensile tests of the anode current collector separately. As shown with the photographs inserted in Fig. 6, the specimens of copper foil current collectors were prepared by decoating the anodes, i.e. removing the active coatings from the anode specimens inside the glovebox. To be comparable to the unexposed anode test results, tensile tests of the current collector specimens were conducted with the same argon protection method. Figure 6 presents test results of the current collectors from unexposed anodes of 4 SOCs (the solid-line curves). The force level of the current collector is apparently lower than that of the anode at each SOC. An unexpected finding is that the force-strain response of current collector also varies in a non-monotonic manner with SOC, i.e. the force level first increases and then decreases along with SOC increase. This trend is quite in line with that of the unexposed anode.

The tensile response of the active coatings can be indirectly obtained by subtracting the current collector contribution from the total response of anode. The calculated force-strain curves of the active coatings are also plotted in Fig. 6. We can see that the curves of active coatings at 4 SOCs almost coincide with one another.

The direct and indirect test results presented in Fig. 6 imply that for the unexposed anode, the mechanical behavior of active coatings (at least the tensile behavior) is unaffected by SOC, while the property change of copper foil current collector is the real source leading to the overall change of anode along with SOC. The new finding differs from the traditional understandings about the influence of lithium ions transportation between cathode and anode. It looks that lithium ions transportation significantly influences the mechanical performance of the copper foil in the anode. Meanwhile, we can see from the test results that SOC also affects the fracture strain of the copper foil. Overall, the foil current collector from the anode of higher SOC is easier to break under mechanical loading.

Tensile tests of the copper foil from anodes after different air exposure durations were also performed in the present study. The results (provided in section Discussion) indicate that air exposure

Figure 4. Results of the electrode tensile tests under argon protection: (a) tensile stress-strain curves of cathode and anode at different SOCs, and (b) tensile test results along different orientations of cathode and anode at SOC of 60%.
almost has no effect on the foil performance even though the SOC is high.

Discussion

Microstructure evolution.—We performed SEM observations towards the electrodes to clarify evolution of the active coating microstructures due to change of SOC and air exposure. During preparing and transferring the SEM specimens, they cannot always be kept inside the ziplock bag, i.e. they have inevitably been exposed to air. An estimate of the total exposure time for an SEM sample is about 10 min.

Figure 7 presents the microscale morphological patterns of the cathodes and anodes at 4 SOCs observed by SEM. For cathode, the LCO particles serve as the main skeleton of the active coating, and the binders fill the gaps among them. The surface of the particle has plenty of stripes, forming a spiral-like shape. This shape implies the multilayer deposition structure of cathode particles. Since it is impossible to use the same cathode sample for microscale observations of different SOCs, we cannot conclude whether the average size of the active particle changes with the SOC increase or not. But it looks true that the morphology of the cathode active stays unchanged for all the SOCs.

Comparatively, the anode coating particles made of graphite have irregular shapes. The large secondary particle mainly consists of small primary particles. At 0% SOC, the surface of the graphite is flat and smooth, while along with the SOC increase, the primary particles start to swell and protrude on the surface of the large graphite. The volume increase of the graphite particle is attributed to the lithium-ion intercalation. At 60% SOC, small crystal clusters emerge on the boundary of the graphite pieces. It looks that the oxidation side reaction occurs most likely to lithiated graphite, forming the dendritic products on the particle surfaces. At 100% SOC, the dendritic products grow up on most of the particle surfaces and even become the cross-links between the particles. We infer that the growth of the dendritic products due to oxidation reaction is the major reason for the dramatic strengthening of the anodes from charged batteries after air exposure, as shown in Fig. 5b.

Non-monotonic change due to air exposure.—We have come up with a conclusion that the SOC effect of the unexposed anode mainly relates to the tensile behavior change of the copper foil.
current collector in the previous section. Similarly, the air exposure effect of anode can also be analyzed by comparing the mechanical performances of anodes and copper foils in different states. Figure 8a shows the maximum force of the anodes at 4 SOCs vs air exposure duration. It can be seen that the strength of anode at 0% SOC decreases during exposure, while the anodes at other three SOCs exhibit the non-monotonic trend, i.e., first increasing and then decreasing. The same plot for the copper foil current collectors from the anodes at 4 SOCs is shown in Fig. 8b. It can be seen that the strength of the current collector at each SOC only presents a slight decrease with air exposure of the anode. Compared to the tensile strength change of the entire anode, influence of the air exposure on the copper foil is indeed negligible. Such an experimental finding implies that the air exposure effect of the entire anode comes from active coating materials. According to the SEM results in the previous section, oxidation of lithiated graphite should be one of the major reasons that lead to the performance change of the active coating. Malmgren et al. reported the influence of exposure to air on composition of lithiated graphite. They demonstrated that the reactions of volatile electrolyte solvent and lithiated graphite with air contribute most to chemical change of the anode. Their conclusion could be a support for the finding of the present study to some extent. Furthermore, based on the above analyses, we infer that there are two different mechanisms competing with each other during the air exposure of the anode. Besides the strengthening mechanism due to oxidation of lithiated graphite, the other one should be a weakening mechanism due to water vapor. Some reaction products in the coating like lithium hydroxide and lithium oxide will have the deliquescence. This can be demonstrated by the monotonous change of strength of 0% SOC anode vs air exposure. For the anode from fully discharged batteries, the oxidation mechanism should only play an inferior role because only a very small amount of lithiated graphite exists in the active coating. During air exposure of the 0% SOC anode, we did not feel apparent heat generation, but instead, the anode surface became moist gradually. Therefore, it looks that absorbing water vapor in air dominates the performance change of the 0% SOC anode, resulting in the monotonous decrease of the strength along with air exposure.

When the high SOC anode is exposed to air, the lithiated graphite reacts with oxygen and releases a large amount of heat. The products of side reaction generate and precipitate on the graphite particle surface, strengthening the anode surface at the early exposure period. With proceeding of the oxidation, most lithiated graphite materials get oxidized, along which the strengthening mechanism gradually reaches the peak. On the other hand, the water vapor in the air keeps affecting the active coating, and turns to soften its microstructure but increase its ductility. For a relatively long time period, the entire anode becomes weakened. These two competing mechanisms finally lead to the non-monotonic change of tensile behavior of the charged anodes subjected to air exposure.

Three-stage stress-strain behavior.—We observed the unique three-stage feature in the stress-strain curves of both the 100% SOC anodes subjected to air exposure longer than 5 min and the charged anodes subjected to sufficient exposure (24 h), as shown in Fig. 5b. We propose a damage accumulation speculation to explain this feature based on the aforementioned competing mechanisms. The active coating of anode gets oxidized gradually in air, which makes the coating materials strengthened but less ductile. For the 100% SOC anode or the other charged anodes with sufficient exposure, the oxidized coating materials occupy a proportion large enough to initiate local damage (e.g. micro-cracks) at an early stage of deformation. The damage initiation corresponds to the turning point of the stress-strain curve. Due to non-uniform oxidation through the active coating thickness, the damage does not tend to spread rapidly. Instead, it propagates or accumulates in the coating and releases the stress partially. In the meantime, the undamaged coating materials and the copper foil in the anode continue to bear the total elongation, forming an appearance of stress plateau. The oscillation or temporary drop of stress in the stress plateau reflects the random development of the local damage. At the last stage, the remaining portions of the anode together go to hardening until the final global fracture.

We have to admit that the three-stage feature stress-strain behavior is so complicated that the damage accumulation speculation proposed above may be unable to provide a satisfactory explanation. The speculation still needs careful verification with more sophisticated tests and analyses. The present study tends not to concentrate much on clarifying mechanism of the three-stage feature, for which we have to figure out feasible investigation scheme in next steps. Meanwhile, the compressive behavior of electrodes is also important in their mechanical characterization and development of a high-fidelity numerical model for crushing or indentation scenarios of lithium-ion batteries. So it is also necessary to clarify the SOC dependency of compressive behavior for electrodes, which is an ongoing investigation topic in the author’s team.

Conclusions

The present study focuses on the mechanical properties of electrode materials in charged lithium-ion batteries, which aims to address one of the key issues in developing an advanced computational model of batteries. The mechanical behavior change of electrode materials under different states of charge (SOCs) is of importance for the investigation of battery safety under mechanical abuse.

An argon-protected testing method is developed at first to achieve the experimental target. By operating inside a glovebox and sealing with ziplock bags, the sample preparation and the mechanical tests can effectively prevent the interference of air and acquire the real properties of unexposed electrode materials as they stay inside the batteries. By extracting samples from a commercial pouch cell at different SOC and testing with the argon-protected method, we identify the SOC dependencies of the tensile behavior of the unexposed electrodes, which are quite different from what was reported in the existing literature. The tensile behavior of anode changes non-monotonically with SOC but the cathode has no obvious change. To reveal the exact roles of the active coating and the copper foil in the SOC effect of the anode, the tensile tests of the copper foil current collector are designed and performed. It is
eventually found that the SOC dependency of the anode tensile behavior mainly comes from the current collector.

To further identify the influence of air exposure on the mechanical properties of electrodes, we performed a series of tensile tests for the electrodes at low to high SOCs with different durations of exposure to air. It is recognized that the influence of air exposure on tensile behavior of anode is very significant while the cathode is almost not affected. For the charged anode, the variation of stress-strain response due to air exposure is non-monotonic. Based on the tensile test results and SEM observation of exposed anodes at different SOCs, we propose two competing mechanisms to explain the air exposure effect of the anode, i.e. a strengthening mechanism.

Figure 7. SEM photographs (5000× magnified) of cathode and anode active coating under various SOCs.
due to lithiated graphite oxidation and a weakening mechanism due to water vapor absorption.

The present study projects a meaningful insight into the varying rules of the mechanical behavior of electrode materials and the underlying mechanisms. Strong experimental evidence is provided for further evaluating the deformation tolerance and damage risk of electrodes in batteries at different SOCs. They could also become a foundation for systematic investigation on the mechanical and chemical mechanisms behind the complicated phenomena.

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