Analysis of the experimental method of cyclic aging processes for batteries of the sweeping robot

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Abstract. A lithium-ion battery begins aging since it is made available, with a variety of secondary reactions taking place inside it, and this has an impact on the battery's safety and performance. Therefore, it is necessary to conduct cyclic aging experiments on batteries under various conditions. In this study, 4 stresses are chosen, ambient temperature (T), constant charging current (i_1), end-of-charge voltage (V_1), and constant discharging current (i_2), with three levels chosen for each stress, and a experimental method is devised for aging batteries, serving as not only the basis for studying the issue about the aging of batteries under the effect of multiple factors, but also the precondition for devising an accelerated battery-aging experiment.

Keywords: A lithium-ion battery; accelerated battery-aging experiment; process of aging.

1. Introduction

Since it came out, a lithium-ion battery has begun the process of aging, which is reflected in capacity attenuation and internal resistance increase. The aging of a unit cell will affect the overall performance of its whole system, including energy, power, temperature rise, and safety. Firstly, a battery system is made up of several unit cells in serial and parallel connections, and as a result, an attenuated capacity of a unit cell will have a direct impact on the energy that the battery system can provide after having been charged once. Secondly, the inconsistency in instant capacity attenuation among different unit cells will further intensify the energy attenuation in the battery system. Thirdly, because a cell has internal resistance in itself, there will be a fraction of voltage during discharge, and when the currents carried are the same, the internal resistance in an aged cell will increase, leading to a bigger fraction of voltage, thus affecting the power and performance of the system. Fourthly, the rate of generating heat in a cell is in direct relation to its internal resistance, and when the current is the same, the increase in the internal resistance of an aged cell will speed up the generation of heat in the cell, thus having an effect on the rise in the temperature of the system. Finally, the aging process in a cell is accompanied with a variety of secondary reactions, and these secondary reactions will affect the chemical composition and physical structure inside the cell, thus affecting the safety and performance of the battery[1~5]. Therefore, it is necessary to do cyclic aging experiments on batteries under various conditions. In this study, in order to reduce experimental costs, an experimental method for aging batteries under these conditions has been devised, for 4 different factors, with three levels chosen for each factor.

2. Description of the method

2.1 Overview of the method

During the use of a battery, there are many stress types that can have effects on its aging, including ambient temperature, humidity, mechanical pressure, radiation, electric current, electric voltage, and SOC range. However, among these many factors, ambient temperature and the electric stress during its use are the main ones in its aging. For example, during the routine processes of charging at a constant current and a constant-voltage (CCCV) and discharging at a constant current and a constant-voltage (CCCV), the main stresses in the aging of the battery include ambient temperature (T), constant charging current (i_1), end-of-charge voltage (V_1), constant-voltage charge duration (t_1), constant discharging current (i_2), end-of-discharge voltage (V_2), and constant-voltage discharge duration (t_2), as shown in the Fig.1.

It needs to be noted that, heat is generated during the process of charging and discharging a battery, resulting in the actual temperature of the battery's body being slightly higher than its ambient temperature. In order to obtain the information about more accurate effects of temperature on the aging of the battery, it is necessary in the process of study to use the actual temperature of the battery. However, the rate of producing heat in the battery relates to it internal resistance, and its internal resistance varies with SOC, and as a result, the actual temperature of the battery will fluctuate over time during charge and discharge. In addition, it is found in a preliminary experiment that, during forced convection at 25° (in a thermostat), in the process of charge and discharge at a magnifying power of 1C (CCCV-CCCV), the average temperature of the battery's body is less than 2°C higher than the ambient temperature, and the difference between them will be smaller if the magnifying power is low. In order to reduce the complexity of the study, in this experiment, an ambient temperature is used instead of the actual temperature of the battery's body to study the effect of temperature on the aging of batteries.

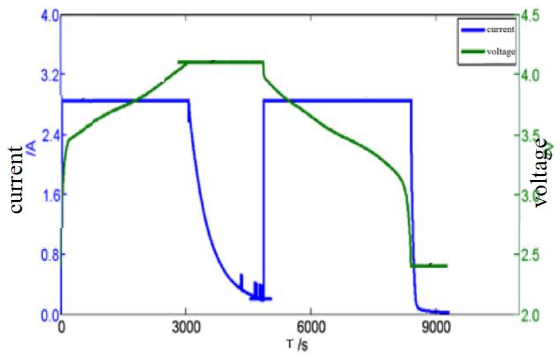

Fig.1 The schematic diagram of conventional constant-current constant-voltage (CCCV) charge – constant-current constant-voltage (CCCV) discharge

By comparison with studying other exterior characteristics of batteries, such as the issues about electricity and heat, the major difficulties facing the study of aging batteries mainly include:

1. A huge cost in time necessary for carrying out experiments: some batteries have a service life that is expected to be up to 5-8 years, and even longer. Even if the experimental method of accelerating the process of aging is used, it will always take more than half a year to obtain the expected experimental samples and the data.

2. More strict requirements for the consistency among batteries: because there is no way to carry out the aging experiments on the same sample battery in different operating modes, it is necessary to ensure a relatively high consistency among different sample batteries. The consistency among batteries not only manifests itself at the initial stage, but also needs to be maintained during the aging process of the batteries, or there will be difficulties in analyzing the experimental results, and the conclusion will be less reliable.

3. A lack of necessary theoretical guidance on the method of study: empirical guidance currently dominates the study about the aging of batteries, and the difference in experimental methods among different researchers is relatively big, e.g. the selection of stress types, the selection of stress levels. This poses a difficulty for the comparison between the results from different studies, resulting in the existing achievements in research being less worthy of reference.

The relationship between "multi-stress" and the "aging behavior" of batteries can be abstractly defined as the relations between multiple stresses and responses (rate of aging). In the field of statistics, it usually needs to take three steps to study the relations between multiple stresses and responses.

First step: to select stresses. Select the stress types having significant effects on dealing with an issue from several complicated stresses, and remove the stresses that have little effects on experimental results, so as to focus on the effects of major factors on responses.

Second step: to create an empirical model. Reasonably devise an experiment based on the stress types selected in the previous step, create an empirical model based on statistical or empirical methods, and consolidate the parameters in the model, so as to quantitatively describe the relations between stress and the response.

Third step: to create a model of mechanism. Understand the reason for the effects of different experimental conditions on experimental results on the basis of a large quantity of experimental results, clarify the relations between external stresses and the research into the internal mechanism of the matter, and create a model of the mechanism, so as to more accurately describe the relations between stress and response.

Multiple stresses have an effect on the aging of batteries at the same time, and it usually takes the above three steps to tackle the matter of the effects of multiple stresses. These three steps are logically in order of precedence, where, the selection of stresses is to distinguish between different stresses in terms of how important their effects on the aging of batteries are, so that suitable stress types can be selected for creating a model for the aging process. Therefore, the selection of stresses is the basis for follow-up studies. In addition, it also is the basis for studying the experimental method of accelerated aging process to distinguish between different stresses according to their importance to the aging of batteries. Hence, it is necessary to attach most importance to the selection of stresses in studying the relations between the aging of batteries and the stresses.

In this study, a generic operating mode of CCCV charge – CCCV discharge (constant-current constant-voltage discharge) is used as the object of study, and the effects are compared of different stresses on the aging of the batteries in this operating mode. It is concluded from relevant literature that, the stress types to be studied include ambient temperature (T), constant charging current (i_1), end-of-charge voltage (V_1), and constant discharging current (i_2). In order to reduce experimental costs, it is necessary to choose a reasonable policy on experiments, so that main conclusions can be drawn through as fewer experiments as possible.

2.2 Experimental design

There are totally four stress types in this study, relatively large in quantity, belonging to a multi-factor experimental design in the field of statistical experimental designs. Because the relationship between the four stresses to be studied and the aging of batteries is unknown, it is necessary to create a statistical model as the basis for the experimental design. Among many statistical models, variance analysis model is capable of helping better analyze the significance of the effects of factors on the responses, suitable for being chosen as the basic model for this study.

It is already statistically proven that, on the basis of a variance analysis model, and using orthogonal experimental design, the estimates of parameters with perfect accuracy can be obtained through a minimum number of experiments. As one of the optimized experimental methods for multiple factors whereby some of representative sample points are selected from the sample space for carrying out the experiment, orthogonal design is called as such because these representative sample points show orthogonality. Orthogonal experimental design is the main method for partly factorial design, with high efficiency. Simply speaking, orthogonal experimental design just means the method of using the orthogonal table to arrange the experiment, where the orthogonal table is a list of arrangements in order of orthogonality for a multi-factor experiment. In an orthogonal experimental design, the concept of the orthogonal table is very important, and it will always largely reduce the number of experiments, provided that the main conclusions from the experiment are not affected, to choose a suitable orthogonal table. Therefore, orthogonal experimental design is chosen as the method of experimental design for this study.

In the experiment, three levels are chosen for each factor, and it can be learned from analyzing the existing orthogonal table that, $L_9(3^4)$ mixed-level orthogonal table is suitable for this experimental study. Table 1 is a $L_9(3^4)$ orthogonal table, featuring 5 columns in total. The first column covers Experiment No. 1-9, i.e. this table includes 9 sets of experiments; the 2nd - 5th columns are filled with different experimental factors, i.e. the effects of 4 different factors can be studied at most. For the 2nd - 5th columns, there are numbers "1", "2" and "3" in each column, indicating the levels chosen for the factor. Therefore, with the $L_9(3^4)$ orthogonal table, the main effects of 4 different factors can be studied, with each factor seeing three levels. Another advantage of using a $L_9(3^4)$ orthogonal table is that the interaction between factors is evenly distributed to every column, and as a result, this table is capable of eliminating the effect of the interaction between factors to the maximum extent, ensuring the reliability of the identification of main causes.

Table 1. $L_9(3^4)$ orthogonal table

Experiment No.		Column No.		
	1	2	3	4
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

3. Experimental samples

The chemical experiment requires a good consistency between sample batteries. For Samsung 18650 batteries from South Korea, their parameters at factor are highly consistent, with voltage difference less than 0.005 V, internal resistance difference less than 5 mΩ, and capacity difference less than 80 m Ah for batteries of the same production date. Samsung batteries are widely used in notebooks, electric vehicles, and monocycles, good at consistency and stability, and relatively cheap. Therefore, commercially relatively well-proven Samsung 18650 batteries are chosen as the objects of this experiment. The batteries are of SAMSUNG ICR18650-22P type, with the samples as shown in the Fig. 2.

Fig. 2 The experimental samples

The composition of the battery and part of its properties are as shown in the Table 2.

Table 2. Composition and performance parameters of the battery

Composition/performance	Parameter
The material for anode	The material publicized in the battery handbook isLi NixCoyMnzO2
The material for cathode	Graphite
Rated capacity	2200mAh(0.2C discharge, 25℃)
Nominal voltage	3.7V
Maximum discharge current	10A
End-of-discharge voltage	2.75V
Operating temperature range	Charge:0~45℃ Discharge:-20~60℃
Ohmic resistance	≤35mΩ

First, at 25℃±5℃, discharge a single lithium battery at an electric current of 0.2C(A) until it has reached the end-of-discharge voltage of 2.75(V) specified in corporate technical conditions, and then, put it aside for 1h, after which, charge it at a constant current of 0.2C(A) until it has reached the end-of-charge voltage of 4.2(V) specified in corporate technical conditions, and then, change it to the charging process at a constant voltage until the charging current has dropped to 0.05C(A), and after that, stop the charging process, and put it aside for 1h, before repeating charging and discharging it 5 times. Finally, on the basis of its initial capacity and internal resistance, analyze its consistency and statistical characteristics, and select suitable sample batteries for follow-up experiments.

In the experiment, the selection of stress levels is usually based on the two rules: (1) all the levels of a factor are capable of covering the actual range of this factor; ;(2) the levels of a factor should be distributed as evenly as possible. In the experiment, the effects of four stresses on the aging of batteries need to be studied, where three levels are chosen for each stress, and based on the above two rules, Table 3 shows the four stresses under research and the value that each stress level has.

Table 3. Stress types and the level that each stress

Stress	Symbol/unit	Level 1	Level 2	Level 3
Ambient temperature	T/°C	0	25	55
Constant charging current	i1/C	0.2	0.5	1
End-of-charge voltage	V1/V	4.1	4.2	4.3
Constant discharge current	i2/C	0.5	1	2
Stress	Symbol/unit	Level 1	Level 2	Level 3

Randomly distribute the selected four stresses across the $L_9(3^4)$ orthogonal table, as shown in the Table 4. In the order of from the 2nd to the 5th columns are, ambient temperature, constant charging current, end-of-charge voltage, and constant discharge current, respectively.

Table 4. Arrangements for the stresses and their levels in the orthogonal table

Experiment No.		Column No.		
	Ambient temperatureT/°C	Constant charging current i_1/C	End-of-charge voltage V_1/V	Constant discharge current i_2/C
1	0	0.2	4.1	0.5
2	0	0.5	4.2	1
3	0	1	4.3	2
4	25	0.2	4.2	2
5	25	0.5	4.3	0.5

6	25	1	4.1	1
7	55	0.2	4.3	1
8	55	0.5	4.1	2
9	55	1	4.2	0.5

4. Summary

It can be seen from the $L_9(3^4)$ orthogonal table that, totally 9 sets of experiments need to be studied in this study. In order to confirm the experiments can be re-enacted, 2 identical samples for each experiment are provided, and thus, totally 18 sample batteries are needed. It is thus clear that, using this experimental method can reduce the numbers of experiments, and save costs and time.

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