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Effect of Current on Cycle Aging of Lithium Ion Batteries

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Abstract—Nowadays, lithium ion batteries are increasingly spreading in different areas and therefore, it is very important to understand their aging behavior. According to the technical literature, battery aging can be dissociated in calendar aging and cycle aging. Calendar aging, in particular, depends on the temperature and state of charge (SoC). In addition to the previous factors, cycle aging also depends on the current rate, and charge/discharge cut-off voltages. In the literature, only a few papers have considered battery aging as a function of the charge/discharge current rate, but they agree that a higher current rate leads to faster battery aging. In any case, all of the tests have been conducted in a climactic chamber with a constant room temperature. However, even if the room temperature is controlled, for high current rates, the temperature of the battery cell increases, which makes it impossible to distinguish the aging due to the current from that due to the temperature. For this reason, in the present work, the authors focused on the lithium ion battery aging due to the current rate while maintaining a constant battery temperature using opportunely controlled Peltier cells. In this way, an interesting results was obtained, i.e. the cycle aging is not dependent on the current rate.

Keywords— Lithium ion battery, cycle aging, current dependency

1. Introduction

In recent years, lithium ion batteries (LiB) have increasingly spread to different areas, which can be divided into two main categories: stationary [1] and mobile applications [2]. In stationary applications, we can mention the use of these batteries as storage services such as in photovoltaic systems where self-consumption is encouraged, or as uninterruptible power supplies. In mobile applications, the use of LiBs runs from the smallest ones used in mobile phones, notebooks, and tablets to the largest ones used in railway traction and electric vehicles. Of course, these two kinds of applications differ from each other based on the battery utilization, and therefore, different aging behaviors may be present. Therefore, it is very important to understand and model how these devices age over time and which factors contribute to this phenomenon. Many studies on this topic have been conducted, and several aging models and chemical descriptions of what happens to the LiB during aging have been proposed, as well-reviewed in [3]. Nevertheless, all of the research agrees with the fact that battery aging can be dissociated in calendar aging and cycle aging [4], [5]. The first refers to the aging of the battery while it is stored on the shelf, whereas the second is due to the charge/discharge of the battery, i.e., its usage. Calendar aging, in particular, depends on the temperature and state of charge (SoC) as function of the time. In addition to the previous factors, cycle aging also depends on current rate, charge/discharge cut-off voltages, and possibly other factors. In any case, according to the particular aging mechanism the battery can decrease its capacity (capacity fade) and/or increases its internal resistance (power fade). Furthermore, the aging mechanisms can differ for different kind of lithium ion battery chemistries [6], [7]. This means that understanding the mechanisms of battery aging is a very difficult task because many factors contribute to the aging. For this reason, it is very important to analyze these phenomena by considering, as much as possible, only one aging factor at time keeping the others constant.

In any case, both for calendar and cycle aging, many papers state that the main cause of battery aging, from a chemical point of view, are the changes in the electrode/electrolyte interface in the negative electrode. In particular, the so-called solid electrolyte interface (SEI) is responsible for both the capacity fade and the resistance increase, i.e., the power fade. Other factors, including changes in the active material and composition of the electrodes also cause aging, although to a lower extent. The SEI starts to form in the first charge/discharge cycles and, after that, its conversion and growth continues during further cycles and even storage [8]. The temperature plays an important role in both the secondary chemical reactions [4], [9], and SEI composition, change, and growth [10], [11], [12]. In fact, high temperatures lead to an additional and accelerated SEI formation, and hence, capacity loss. High SoC levels also accelerate the SEI growth [13]. Indeed, for the same temperature but different SoC levels, the aging is different. High SoC levels correspond to a high concentration of ions on the electrodes. Therefore, a large potential difference between the electrodes and the electrolyte interfaces leads to chemical reactions, which age the battery. Low SoC levels also causes an increased ageing, due to corrosion of the materials [14]. Other studies have also analyzed the combination of the SoC and temperature in battery aging [15], [16], discovering a nonlinear dependency with time. Conversely, at low temperatures, these phenomena are reduced but the limitation on the diffusion of lithium ions into the SEI and electrodes leads to other phenomena called lithium plating and lithium dendrite growth [17]-[20]. In particular, lithium plating occurs at a low temperature during battery charging. Good reviews of these aging mechanisms can be found in [21], [22].

Focusing, in particular, on cycle aging, in addition to the temperature and SoC level, important factors for battery aging are the charging/discharging cut-off voltages. The authors in [26] showed that high charging cut-off voltages accelerated the aging phenomena, particularly the capacity fade, while low discharging cut-off voltages affected the aging, particularly the power fade [27].

In light of the above, in the literature, it is possible to find several papers where the authors studied both calendar aging and cycle aging considering, in particular, the SoC, temperature, and cut-off voltages as aging factors. Conversely, few studies considered battery aging as a function of the charge/discharge current rate [28]-[33]. In [28], the effect of current rate on the aging is analyzed cycling the battery at different current rates. Anyway, even if the tests are performed in a climatic chamber at 25 °C, the temperature of the battery cell is not controlled and will change with the current rate due to its internal losses. Moreover, high and low SoC levels and the effect of the cut-off voltages also contribute to aging, therefore the contribution due to the current is not deductible. In [29], the authors studied the effect of different kinds of charging protocols on the aging. The room temperature was fixed at 23 °C, but not the temperature of the battery cell. The authors concluded that a slow charging battery was better for healthy charging near the end of the charge. In any case, a lower current leads to a lower cell temperature and, therefore, the results of [29] were also affected by the temperature. In [30], the authors performed some experimental tests at a room temperature of 25 °C, using a climatic chamber, to evaluate battery aging as a function of different charging protocols. Similar to the previous paper, the authors confirmed that high currents had a greater effect on aging. Moreover, they also stated that high charging currents aged the battery more than the discharging ones. Also in this case, the battery temperature depends on the current rate and, therefore, the two effects are not separable with these tests. Moreover, the aging effect due to the high voltages can explain the different aging during charge and discharge, just taking into account that the internal voltage of the battery is higher than the applied one during discharge and lower during charge. In any case, both in [29] and [30], according to the kind of charging protocol, the charging cut-off voltage was reached, and the aging due to both a high SoC and high voltage was not decoupled from the current effect. In [32], other experiments confirmed that high discharging currents affected the aging less than the charging ones, and different charging/discharging cut-off voltages were considered. Finally, in [33], the authors performed different cycle life tests in order to reveal the aging mechanisms of a battery under different charging currents and cut-off voltages with similar conclusions.

In all of these cases, these authors agreed with the fact that a higher current rate leads to faster battery aging, and in some cases, they highlighted that, even if the tests were conducted in climatic chambers, the temperature of the battery cell was not constant, with high currents increasing the temperature. Furthermore, they performed the tests by charging and discharging the battery between the minimum and maximum cut-off voltages. Consequently, it was not possible to understand whether the aging of the battery was really due to the value of the current itself or to the temperature increase and/or the charging/discharging cut-off voltages and low/high SoC levels.

In [28] and [34], the authors state that the cycle aging is independent on the SoC variation, at least the capacity fade. Moreover, testing different cycles it has been proven in [35] that the capacity fade depends on the total moved charge into the battery independently on the shape of the cycle. This is a very important result meaning that at constant temperature, and with the SoC limited between 20% and 80%, for any cycle shape, the aging behavior depends only on the moved charge.

In the present study, the effect of the current on the aging of a lithium ion cobalt oxide (LCO) battery, which is composed of a cobalt oxide cathode and a graphite anode, was analyzed. In particular, this paper focuses only on the effect of the current rate on the capacity degradation. In order to do this, the battery cells under test were set on Peltier cells, opportunely controlled, to guarantee that the temperature of the battery cell was between 30 °C and 20 °C to avoid different aging due to high/low temperatures. In fact, the authors in [7] state that, for the most lithium ion batteries, the suitable and safe working temperature window is between 15 °C and 35 °C. In particular, 25 °C seems to be the best temperature to minimize the aging mechanisms due to high/low temperatures [36]. Furthermore, the cycle tests were also performed by limiting the SoC between 20% and 80% and the maximum and minimum voltages in order to avoid predominant aging effects due to low/high SoC levels and low/high voltage regions. In the next section, the test procedure is thoroughly analyzed, while in section 3, the experimental results are reported and discussed. Finally, section 4 draws some conclusions.

2. Test Procedure

The results reported in this paper are in the framework of a research aiming at realizing a complete model of the aging phenomena of lithium-ion batteries. First, to build an aging model, it is necessary to define the parameters to measure the aging of a cell. In the technical literature, two main effects are linked with battery aging: i) the reduction of the battery capacity and ii) the increase of the battery internal resistance. In this paper, the first is selected to identify the aging of the battery. For this reason, the state of health is defined as follows:

$$\mathrm{SoH} = \frac{C}{C_{in}} \tag{1}$$

where C is the amount of charge that the battery is capable of supplying during a discharge, and C_{in} is the amount of charge given by the battery at its first use. It is worth noting that the amount of charge that the battery gives as an output depends on the working conditions. For this reason, it is necessary that the measurement of the capacity is always performed under the same conditions (i.e., the same current profile, cut-off voltages, and same working temperature). In particular, all the capacity measurements were performed at 20 °C and with a constant current constant voltage discharge profile [30].

The batteries used for these tests are LCO cells (8773160K) manufactured by General Electronics Battery Co. Table 1 lists the characteristics of this cell.

The test procedure can be divided in two phases: capacity measurement and aging cycles. The capacity measurement is performed at the beginning of the aging test to measure the initial capacity C_{in} of the cell and after each aging cycles phase to measure the capacity fade.

Item	Specifications
Rated Capacity (C)	10 Ah
Rated Voltage	3.7 V
Standard Charge Current	0.2C
Max Charge Current	1C
Charge cut-off Voltage	4.2 V
Discharge Current	Continuously: 10C; Max: 15C
Discharge cut-off Voltage	2.75 V
Size L × W × H [mm]	152 × 72 × 9

Table 1. BATTERY SPECIFICATIONS

2.1 Capacity measurement

Firstly, the cell under test is charged at constant current at 10 A (1C) until the voltage reaches the charging cut-off value of 4.2 V, and then the charging process is continued at this constant voltage until the charging current is lower than 0.01C. Secondly, the cell is discharged at 10 A (1C) until the voltage reaches the discharge cut-off value of 2.75 V, and then, this constant voltage value is kept constant until the discharge current is lower than 0.01C. The integral of the current during the discharging phase T_d represents the actual capacity of the cell C in Ah:

$$C = \frac{1}{3600}\int_{T_d} i(t)dt. \qquad (2)$$

After that, the cell is fully charged following the previous procedure and, then, discharged at 1C (i.e. 10 A) moving a total charge of 8 Ah, i.e. until the SoC level is 20%.

2.2 Aging cycles

This phase consists of a sequence of charging/discharging cycles at a constant current rate but in limited SoC and voltage ranges. In this research, the authors had the goal of separating the effects of the influencing factors (temperature, low/high SoC level, and low/high voltage regions) by keeping all these factors constant but one (current rate). Moreover, the constant factors were kept at values not strongly influencing the aging of the battery. In a previous work [35], the effect of the duty cycle on the cycle aging was analyzed. For this reason, different cycle shapes were tested using the same current (lower than the rated one 0.8C), working in the medium voltage region, and in a SoC range between 20% and 80%, and keeping the cell temperature between 20 °C and 30 °C. The results of these tests showed that the aging depended only on the moved charge q and did not depend on the cycle shape.

It is important to highlight that, often, in the literature, the aging is expressed as a function of the number of cycles or of the time. This requires the definition of a typical cycle and, moreover, implies that all the cycles have to be equal. Anyway, if the aging depends only on the moved charge and not on the cycle shape, according to [35], it is possible to express the aging of the battery as a function of the moved charge q expressed in Ah, i.e. the integral of the amplitude of the current:

$$q = \frac{1}{3600}\int_0^t \left|i(\tau)\right| d\tau. \tag{3}$$

In this way, we can avoid confusion about the equivalence between the number of cycles and the related time to quantify the aging of the battery. In fact, the aging time depends on the cycle shape. On the contrary, according to the results for which the capacity fade of the battery does not depend on that factor, the moved charge q is an unambiguous indicator of the battery usage.

In this study, the dependence of the aging phenomenon on the current rate was investigated. In order to isolate the effect of the current from the other factors, different tests were performed at different constant charge/discharge currents working in the same conditions of [33], i.e. working in the linear region of the battery limiting the SoC between 20% and 80% and avoiding the low/high voltage regions. Starting from the 20% of the SoC the charge current is applied up to move 6 Ah. After that, the current is reversed discharging the battery up to move other 6 Ah. In all the tests, in order to avoid low/high voltage regions, the battery voltage is limited between 3.45 V and 4.05 V. Consequently, if the voltage limits are never reached in either the charging or discharging phase, then for each cycle always 12 Ah are moved. Otherwise, if at least one of the two voltage limits is reached, then the voltage drop due to the internal resistance of the battery implies different moved charges (less than 12 Ah) in the cycle according to the current rate. In any case, this is not of interest because, as stated before, between the 20% and 80% of the SoC, the capacity fade is dependent only on the moved charge. In this way, we are sure that the aging mechanisms related to low/high SoC levels and low/high voltage values are negligible. The moved charge in each charging/discharging cycle can thus be different, but expressing the age as function of the moved charge this issue is solved. In practice, two cycles moving a certain quantity of charge have the same aging effect of one cycle moving double of the charge of the previous cycles.

It is worth noting that when repeating the tests at different increasing currents, the cell temperature could significantly increase even if the ambient temperature was controlled (i.e., if the tests were performed in a climate chamber). For this reason, to keep the battery cell temperature not higher than 30 °C, the battery cells were cooled by means of Peltier cells attached to bottom side of the pouch cell. The cell temperature was measured on the top side of the pouch cell where the temperature will be the highest one between the two. Since the used pouch cell is really thin (i.e. 9 mm), we expect that the temperature gradient is limited. This aspect will be verified later. In this way, it was possible to separate the aging effect due to the current from the aging effect due to the temperature.

The main contribution of this paper involves this test procedure, and the very important results obtained can be explained on the basis of this separation of the aging effects. Indeed, it is a common belief that a higher battery current leads to faster battery aging. The results of this study showed that if the cell temperature is controlled and both the SoC and the voltage are limited, working at higher currents does not imply faster aging, but, aging seems independent on the current rate. The practical evidence that using batteries at high current rates reduces their own lifetime is due to the increasing of the temperature and not to a direct effect of the current.

3. Experimental Setup and Results

According to the procedure described in the previous section, three lithium ion battery cells (8773160K) manufactured by General Electronics Battery Co. were tested. These tests were performed at the Department of Electronics, Information and Bioengineering of the Politecnico di Milano using a 100-A booster (VMP3B-100) connected to a potentiostat (SP-150), both manufactured by Biologic Science Instruments, and controlled by a PC via Ethernet with EC-LAB software (Fig. 1a).

Fig. 1b shows the cooling system of the battery. It was composed of a heatsink with four fans, three Peltier cells placed over the heatsink and fed by a DC voltage source, and the lithium ion battery cell under test placed over the Peltier cells. In particular, the aging test performed at 8 A (0.8C) was the same as that conducted in [35], where neither the Peltier cells nor the fans were used. In that case, it was not necessary because the temperature increase was limited by the low current value between 20 °C and 30 °C. For higher currents without heatsink the temperature increase is not limited. As example, Fig. 2 shows the temperature behavior of one battery cell cycled at 8 A and another one cycled at 50 A with neither heatsink nor Peltier cells. The cell temperature reached more than 50 °C for the test performed at 50 A.

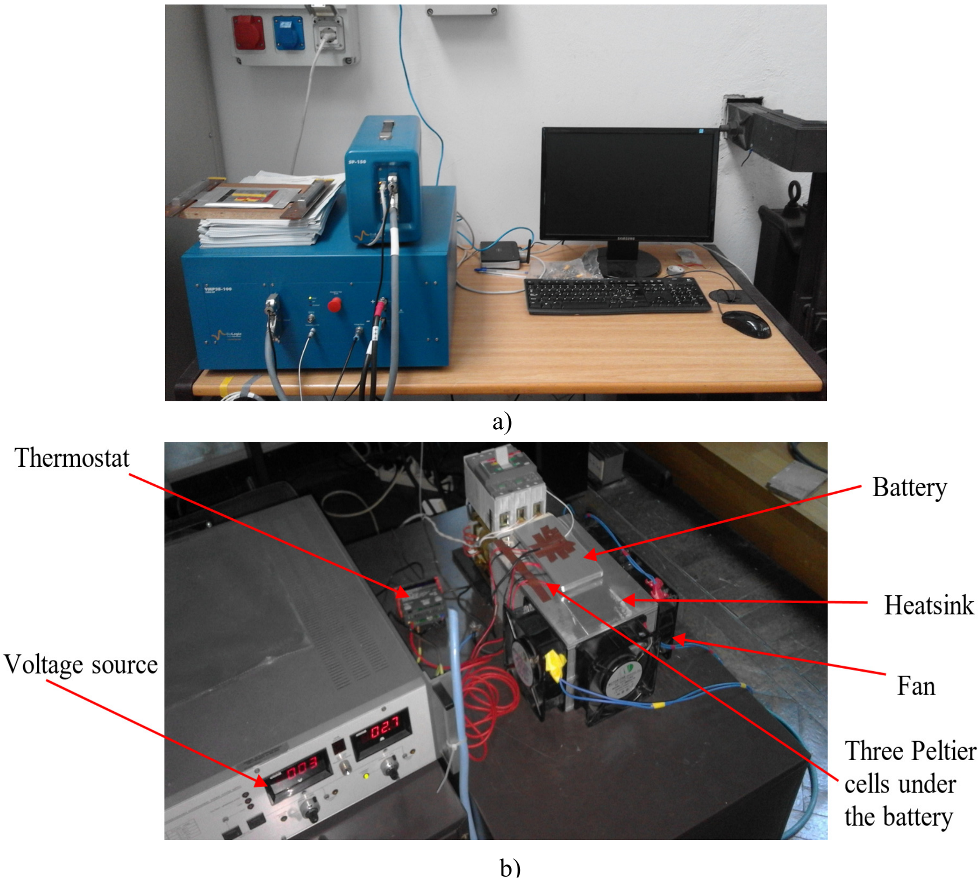

Fig. 1. a) Experimental setup; b) Cooling system with lithium ion battery

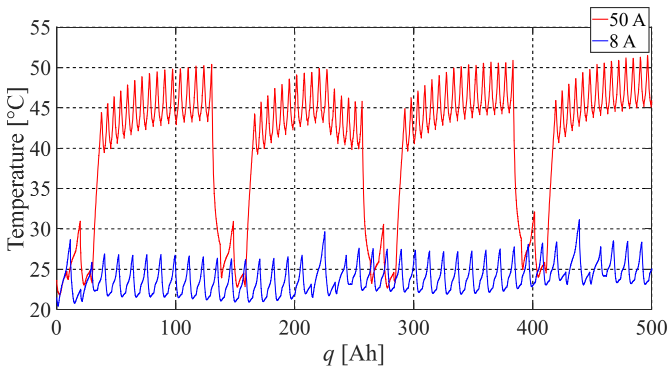

Fig. 2. Temperature of battery cell at 50 A (red line) and 8 A (blue line) with neither heatsink nor Peltier cells

Instead, for the new tests performed at 25 A (2.5C) and 50 A (5C), the current of the three Peltier cells was regulated to maintain the temperature of the battery around 30 °C (Fig. 3) during the aging cycles. After a fixed number of cycles, the system performed a measurement of the cell capacitance following the procedure described in the previous section. The current used for the capacity measurement is 10 A (1C) and, consequently, during this measurement the cell temperature decreases. A thermostat opportunely tuned turned off the Peltier cells when the battery cell temperature reached 20 °C, allowing the capacitance measurement at 20 °C.

With this procedure, it is possible to state that the temperature effect on the ageing for the tests at different current rates is practically the same and can be neglected in the comparison.

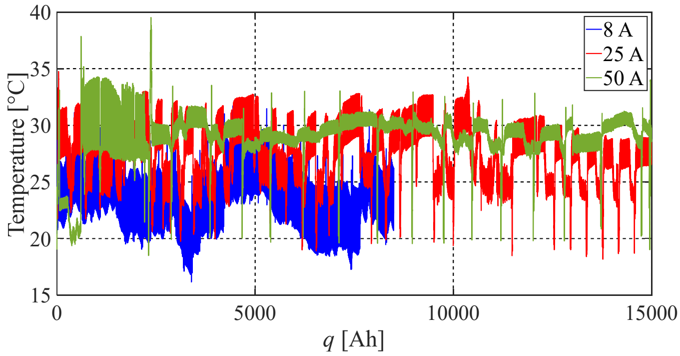

Fig. 3. Temperature of battery cells under tests at different current rates

In order to better clarify this hypothesis the weekly moving average of the temperature of the batteries under tests is shown in Fig. 4. From this figure it is possible to notice that for all the cases the average temperature is always in the safe interval (20 °C - 30 °C) and that the difference among the cells is around 5° C.

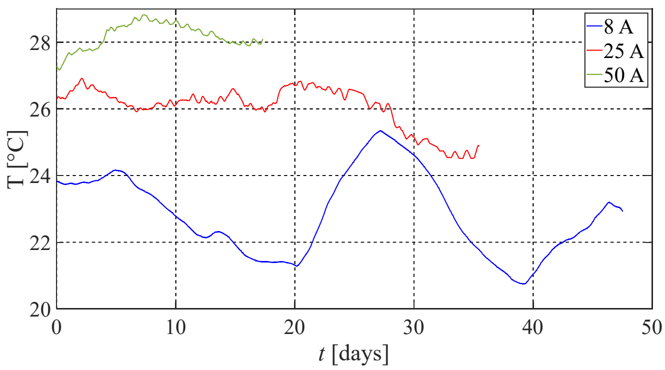

Fig. 4. Moving average of the temperature of battery cells under tests at different current rates

As previously said, all the temperatures reported in Fig. 3 and Fig. 4 are the ones measured on the top side of the lithium ion cells. Since along the thickness direction the temperature gradient could be relatively large, a dedicated test was performed measuring the battery temperature on both sides of the cell. The comparison between the temperatures measured on the top and bottom sides of the cell during the aging cycles at 50 A is shown in Fig. 5. From this figure, we can note that the temperature gradient is around 5 °C.

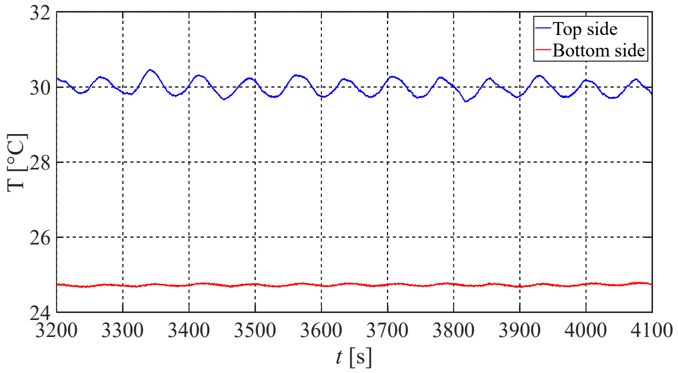

Fig. 5 Top and bottom side temperatures of battery cell under test performed at 50 A

Considering a uniform distribution of the temperature gradient along the thickness of the cells, for the two tests performed with the Peltier cells, an average temperature of the cell 2.5°C lower than the measured on the hottest side can be estimated. The weekly moving averages of the temperatures, corrected taking into account the spatial temperature gradient, are shown in

Fig. 6. We can see that the temperatures are much nearer each other and nearer to the best temperature, i.e. 25 °C. This fact makes the temperature effect on the aging negligible.

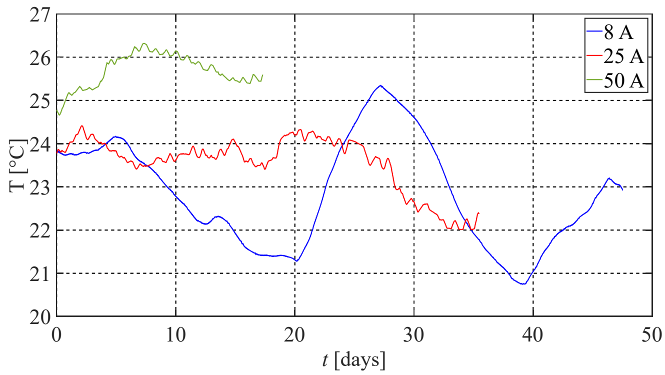

Fig. 6. Moving average of the temperature of battery cells under tests at different current rates considering the spatial average temperature for the tests performed using the Peltier cells

Fig. 7 shows an example of the voltage profile of the cell tested at 50 A during the aging tests. It is worth noting that, during the aging cycles phase, the voltage of the cell is always between 3.45 V and 4.05 V. Thanks to this voltage limitation, we can state that both the low/high SoC and low/high voltage effects can be avoided.

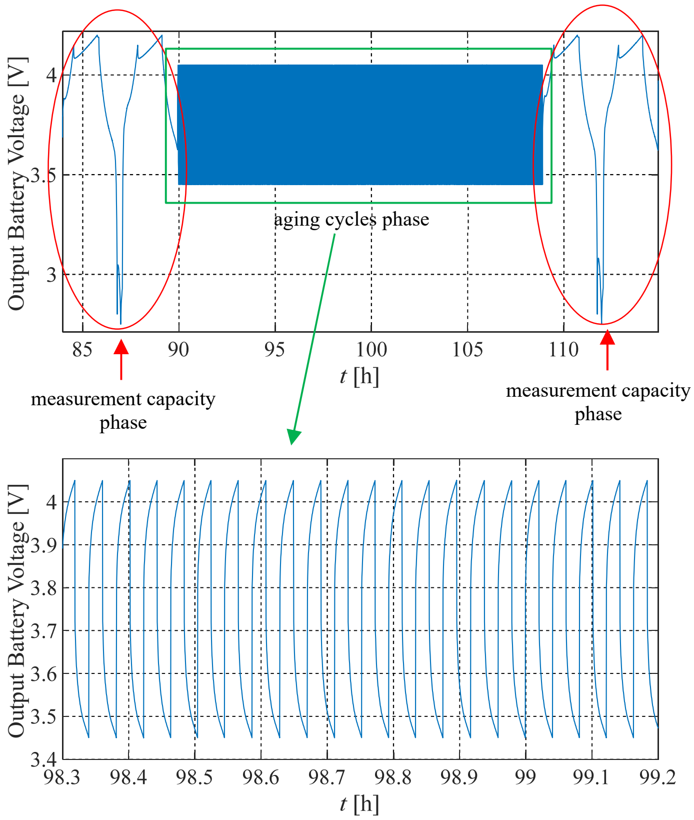

Fig. 7. Voltage profile of cell tested at 25 A

In this way, we could analyze and compare the battery aging only due to the different current rates. Fig. 8 shows the capacity fade as a function of the moved charge q, both expressed in Ah, of the three cells.

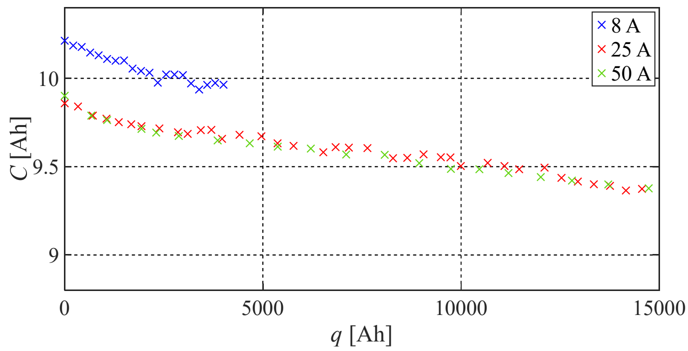

Fig. 8. Aging tests of battery cells

The authors are aware that the number of samples of the cells used in this work is not significant from a statistical point of view. Nevertheless, the aim of the work is not to find the right parameters to represent the behavior of a single cell, but is to search for a general trend describing the global effect of current rate on lithium ion batteries aging. Therefore, the capacity fade was divided for each test by the initial values of the capacities obtaining the SoH. In particular, the latter was performed using the initial value of the interpolant function to make the result independent on an *activation phenomenon* affecting the batteries behavior during the first cycles after resting for long periods. Moreover, although equal lithium ion battery cells, taken from the same batch, were used for the tests, there were some differences between them, due to both manufacturing reasons and calendar aging, which can be mitigated through the calculation of the SoH itself. The calendar aging is due to the fact that the tests were performed in time series. According to different papers [37], [38] the calendar aging can be modeled as a function of the square root of the time. This means that at the beginning of the life the calendar aging is much faster than later. In [39]-[41] some experimental data are reported for different lithium ion batteries. It is possible to recognize that at the beginning of the life (when the cell is built) even one month yield about 2% of aging in the optimal condition of SoC and temperature. After one year the calendar aging is much less fast. In fact, the same window time of one month yield an aging about 0.1%. Since our tests started one year later the cells were bought and the lasting of the tests, as reported in Fig. 4, are between 18 and 48 days, it is possible to consider the calendar aging to be the same for all the tests and negligible because less than 0.1%.

In [35], the interpolant function used for characterizing the aging behavior, as a function of the moved charge, was as follows:

$$C(q) = C_i - a\sqrt{q} \tag{4}$$

where C_i is the initial capacity of the interpolant function, and a is the aging coefficient. In the present study, on the basis of longer tests, the interpolant function was improved as follows:

$$C(q) = C_i - a\sqrt{q} + bq - cq^2. \tag{5}$$

This is because, in [35], the aging tests performed with a current rate of 8 A were very long and only a small part of the aging curve was explored. In the new aging tests, which were performed with higher current rates, and hence faster, we could extend the total moved charge. From Fig. 8, in particular looking at the curves performed at 25 A and 50 A, it is possible to see that, after a certain value of moved charge, the aging curves become almost linear, and then the slope changes again. This is the reason for adding both the linear and square terms in (5).

By fitting the experimental results for each test through (5) a very good agreement between the experimental data and fitted ones, as reported in Fig. 9, can be recognized. The coefficients of the related interpolant aging functions are reported in Table 2. Looking at Fig. 9 and at the coefficients of those interpolant functions, it is possible to note that the aging trend seems to be the same for all the tests. In particular, for the tests performed at 25 A and 50 A the two behaviors are practically the same. The capacity fade of the aging test performed at 8 A starts with a higher initial capacity but, also in this case, the overall trend seems the same of the other two aging tests.

I [A]	C_i [Ah]	a [$Ah^{1/2}$]	b	c [Ah^{-1}]
8	10.24	$5.33\cdot10^{-3}$	$2.73\cdot10^{-5}$	$1.50\cdot10^{-9}$
25	9.90	$4.93\cdot10^{-3}$	$2.88\cdot10^{-5}$	$1.69\cdot10^{-9}$
50	9.90	$4.89\cdot10^{-3}$	$1.78\cdot10^{-5}$	$0.92\cdot10^{-9}$

Table 2. PARAMETERS OF THE AGING FUNCTIONS

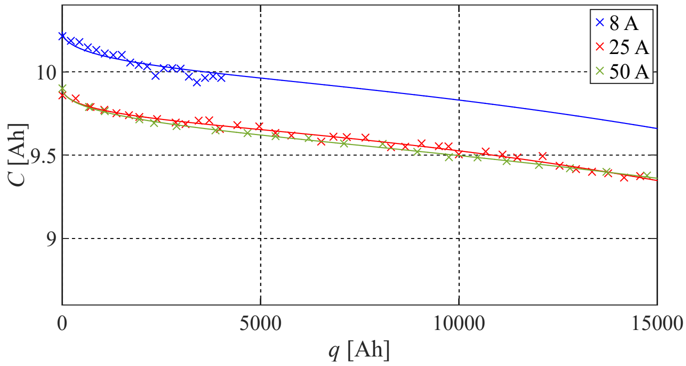

Fig. 9. Interpolation of aging data

Then, as previously stated, each experimental aging curve has been divided by using the initial value C_i of the related interpolant function obtaining the SoH, and finally, we can compare the aging behaviors due to the different current rates. The coefficients of the SoH interpolant functions are reported in Table 3.

I [A]	a/C_i [$Ah^{-1/2}$]	b/C_i [Ah^{-1}]	c/C_i [Ah^{-2}]
8	$5.21\cdot10^{-4}$	$2.67\cdot10^{-6}$	$1.47\cdot10^{-10}$
25	$4.98\cdot10^{-4}$	$2.91\cdot10^{-6}$	$1.71\cdot10^{-10}$
50	$4.94\cdot10^{-4}$	$1.82\cdot10^{-6}$	$0.93\cdot10^{-10}$

Table 3. COEFFICIENTS OF THE SOH INTERPOLANT FUNCTIONS

As expected, the coefficients of the SoH aging functions are very similar each other for all the tests. This means that it is possible to interpolate all the experimental data using only one SoH aging curve. For this reason, we can average the coefficients of Table 3 and according to (1) and (5) the following SoH aging function is obtained:

$$\mathrm{SoH}(q) = 1 - 5\cdot10^{-4}\sqrt{q} + 2.5\cdot10^{-6}q - 1.4\cdot10^{-10}q^2. \tag{6}$$

where q is expressed in Ah. Fig. 10 shows the SoH aging functions for all the aging tests with the SoH interpolant aging function reported in (6). From the analysis of this figure, it can be stated that the cycle aging trend due to different currents is the same and depends only on the moved charge.

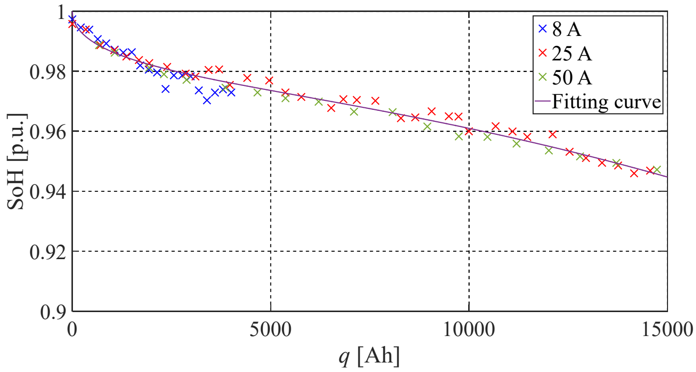

Fig. 10. SoH aging functions

In fact, as discussed in the introduction, keeping the battery temperature in the appropriate interval and limiting both the SoC and charge/discharge voltages it was possible to highlight the specific effect of the current rate evidencing that there is no direct effect of the current rate, at least up to 5C, on the aging. According to the battery specification reported in Table 1 this kind of cells can be discharged up to 10C. The choice to limit the current rate to 5C is due to the fact that for higher current rates the voltage drop over the internal resistance becomes comparable with the voltage range usable for the battery. In such a way, the voltage limits would be met fast provoking aging cycles with high frequency. This can lead to other aging phenomena to be avoided.

Moreover, from the results, we can see that the aging tests was performed up to 95% of the SoH for reasons of time. Therefore, based on the actual results, we can state that the current rate does not affect the capacity fade on cycling above 95% of the initial capacity for moderate current rates over a limited SoC window and temperature interval between 20 °C and 30 °C. On the contrary, previous works on this topic failed in separating the current rate effect from the temperature rising effect leading to the wrong conclusion that high current rates directly imply faster aging.

4. Conclusion

In the present study, the effect of the current rate on the cycle aging of lithium ion batteries was analyzed. The aging phenomenon depends on many factors, including the low/high SoC levels, charging/discharging cut-off voltages, temperature, and current rate. The current rate directly influences the battery temperature due to losses inside the battery. In particular, high charging/discharging currents imply a significant increasing of the battery temperature. Therefore, in order to estimate the effect of the current rate on battery aging, it is not correct to maintain a constant room temperature using climatic chambers as done in other works presented in the literature.

For high currents, in order to separate the effect of the temperature increase from the effect due to the current rate on the aging phenomenon, in the present work, the battery cells under test were set on Peltier cells opportunely controlled, to maintain the temperature of the batteries, as much as possible, in the safe temperature range between 20 °C and 30 °C. Furthermore, the cycle tests were performed by limiting both the SoC variation between 20% and 80% and the maximum and minimum voltages.

The results of the performed tests show that the capacity fade is independent on the current rate, for moderate current rates (up to 5C) and up to 95% of the initial capacity, if the battery temperature is kept within the appropriate interval and the cell is not stressed from voltage and SoC point of views. In this paper, in order to obtain the qualitative variation law of the SoH as function only of the current rate, the authors followed a procedure to identify the aging effect of this aging factor by reducing to a minimum the aging effect of the other factors (i.e. voltage, temperature and SoC).

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