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Applications of high power density lithium ion batteries

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Abstract

In 2003, we developed a new type of lithium ion battery for the light vehicle application, in which 14 cells of 7 Ah were integrated into a battery pack. It has the high rate discharge capability up to 5*C* rate (35 A), a energy density of 74 Wh kg^{-1}, and the low temperature discharge capacity at −5 °C more than 90% of that at 25 °C. The life cycle test of 100% depth of discharge (DOD) at 35 °C showed the capacity fading around 10% after 500 cycles, which confirmed much longer practical life than 2 years.

Recently, we have developed a new high power cell. It has the capacity of 5.5 Ah, and has the output power density of 3000 W kg^{-1} at 50% state of charge (SOC) and at 25 °C for 5 s discharge basis, and the input power density of 2200 W kg^{-1} at the same conditions. The new cells showed much less increase in direct current resistance (DCR) in both the cycle life test and the storage life test than the cells developed before, which consequently implied much longer calendar life than our previous ones developed in 2000.

Keywords: Direct current resistance; Lithium ion battery; Calendar life

1. Introduction

We have been developing lithium ion batteries since the beginning of 1990s, as a member of national project of Japan, named The Development of Dispersed-Type Battery Energy Storage Technology. We have been concentrating on the manganese-based positive electrode materials in the project [1]. By utilizing the results developed in the project, we have released large capacity cells of 90 Ah for electric vehicle (EV) application [2] and high power cells of 3.6 Ah for hybrid electric vehicle (HEV) application [3]. They were applied to commercial vehicles in 2000 [4]. Among them, we expected the application of high power density lithium ion batteries to be the most promising one, for it takes the advantage of the most outstanding feature of lithium ion batteries quite well. Recently, we have developed two types of improved lithium batteries. One is the high energy density and medium rate battery for light vehicle application, and the other is the high power density cell for the HEV application.

Fig. 1 is a Ragone plot showing specific energy density and specific power density for various kinds of secondary batteries in module basis. The high energy density performance of lithium ion batteries is explicitly illustrated in the figure. The plots of “HEV” and “pure-EV” are those that we developed in 2000 as described above. These two plots prove that the lithium ion batteries are flexible enough to be designed from high power specification to high energy specification. The plot of “light vehicle” in Fig. 1 corresponds to that we developed recently and it also proves the flexibility mentioned above. The features and performance for it besides with that for the new high power density cell will be discussed in this paper.

2. Experimental

The cell chemistry of the lithium battery consisted of manganese-based material positive electrode and hard carbon negative electrode. The positive electrode was formed on an aluminum foil by coating with an active material mixture containing the active material, the conductive material and the binder. The negative electrode was formed on a copper foil by coating with an active material mixture containing the active material and the binder. The electrolytic solution consisted of lithium hexafluoro-phosphate and a mixture of

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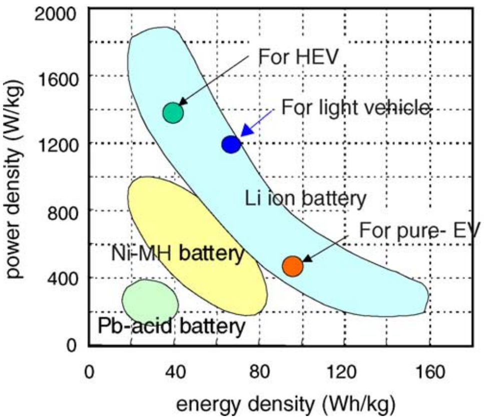


Fig. 1. Comparison of various secondary batteries.

organic carbonate solvents. The separator was an ordinary polyolefin micro porous sheet. The cell shape was cylindrical and the positive electrode, the separator and the negative electrode were wound into a wound electrode. The wound electrode was put into the cell casing and crimped with the gasket and the cap after the injection of the electrolytic solution.

The rated capacity for the light vehicle cell was measured at 25 °C by a discharge current of 7 A down to 2.7 V after the CC–CV charging at 7.5 A constant current up to 4.2 V of constant voltage for 3 h in total time. The rated capacity for the new HEV cell was measured at 25 °C by a discharge current of 2 A down to 2.7 V after the CC–CV charging at 6 A constant current up to 4.1 V of constant voltage for 2.5 h in total time.

We figured the power profile, or input/output power–state of charge (SOC) diagram, to evaluate the power capability of the high power density cell. The method is a kind of extrapolation and the procedure is as follows:

1. Apply a constant current of a certain value I_1 to the test cell of a certain SOC.
2. Measure the cell voltage after a certain duration of time, for example, 5 s.
3. Repeat (1) and (2) at the increased current values of I_2, I_3, or further.
4. Plot the cell voltages against I_1, I_2, I_3, or further to draw an *I*–*V* curve.
5. Extrapolate the *I*–*V* curve, obtained at (4), down to the cut off voltage of discharge, for example, 2.5 V. Then the $I_{\max}(1)$ is determined.
6. Calculate $P_{\text{out}}(1)$ as the product of 2.5 V and $I_{\max}(1)$.
7. Move to another SOC and repeat from (1) to (6), then $P_{\text{out}}(2)$ is obtained.
8. Plot all the $P_{\text{out}}(n)$s against SOC, then the power profile for the output is drawn.
9. For the input power, similar procedures from (1) to (8) are applicable; however, 4.2 V should be used as not discharge but charge cut off voltage in (5) and (6).

Pulse cycle test is a simplified test pattern to simulate the real load pattern of HEV, and it was adopted to predict the HEV battery life affected by the stress of the iterative charge–discharge cycles in a vehicle operation. We used a rather shallow duty cycle mode of 1% SOC/cycle.

We calculated the DCR as the slope of a *I*–*V* curve obtained by following the procedure described above in (1)–(4). DCR is thought to be in the reciprocal relationship with the output or the input power; therefore it will be a good scale to estimate the power capability of the battery.

3. Light vehicle battery

The performance requested by the light vehicle application is considerably different from that by the four-wheel vehicles; the battery is almost naked to the environment, therefore, the battery temperature becomes nearly equal to the environmental temperature and the shock impact to the battery is almost the same as that to the vehicle wheels; extremely cold temperatures, such as below −10 °C, are not supposed; the load pattern is not continuous but rather pulsative though it is a kind of pure electric vehicle.

The cell and module battery were developed taking these differences into considerations. Table 1 shows the specifications for the light vehicle application cell. The dimensions for it are 40 mm in diameter and 125 mm in length, and the mass for it is 350 g. Therefore, the specific energy density is 74 Wh kg^{-1} and volumetric energy density is 165 Wh dm^{-3}. Rated capacity is 7 Ah and high rate discharge up to 5*C* rate, namely 35 A/cell, is capable. Even at 0 °C or less, light vehicle is requested to have almost the same mileage as 25 °C. We improved the low temperature discharge performance at −5 °C by adjusting cell design. The results are shown in Fig. 2. The low temperature performance down to −5 °C was improved enough to keep more than 90% of the discharge capacity at 25 °C. Fig. 3 shows the results of charge–discharge cycle life test conducted at 3.75 A (1/2*C* rate) CC charge and 4.2 V CV charge up to 3 h in total, and 30 A discharge down to 100% depth of discharge (DOD). The discharge capacity after 500 cycles at 35 °C remained around 90% of the initial capacity, which confirmed much longer life than 2 years in the practical usage.

Table 1
Specifications of light vehicle cell

Item	Specification
Cell chemistry (±)	Mn-based/hard C
Nominal voltage	3.7 V
Rated capacity	7 Ah
Dimensions	
Length	125 mm
Diameter	40 mm
Mass	350 g
Continuous max. discharge current	5 CA (35 A)

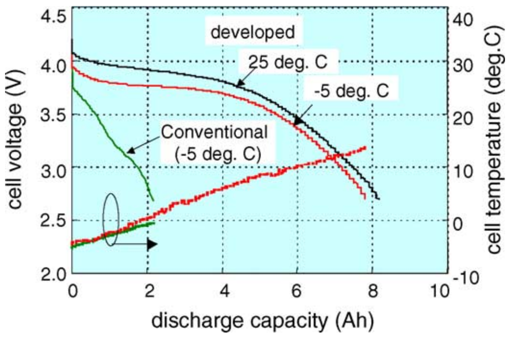


Fig. 2. Improvement of 30 A discharge performance.

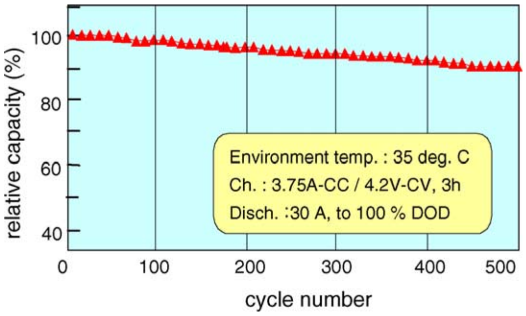


Fig. 3. Life cycle test of light vehicle cell.

Since the capacity, the power capability, the low temperature performance at −5 °C and the cycle life performance met the target for the light vehicle application, 14-cell module battery for the application was designed, consisting of two-parallel cells connected in seven-series. The rating for it was 14 Ah–26 V, the dimensions were 95 mm in depth, 370 mm in length and 147 mm in height, and the mass was 6 kg. The light vehicle is a kind of electric scooters and already launched into the market by Yamaha Motor Co. [5]. Although it is a small vehicle, it is surely classified as a pure electric vehicle driven only by electric power with zero emission. We evaluated the merit for the electric scooter against a conventional ICE scooter with the life cycle assessment (LCA) method. Table 2 shows the prerequisite for the LCA. One charge mileage for the electric vehicle is 32 km and total mileage by the end of the life is 16,000 km. Energy efficiency of charging is 85%. The ICE capacity is assumed to be 50 ml, total mileage by the end of the life is also supposed to be 16,000 km, the same as the electric scooter, and the average fuel economy is 63 km dm^{-3}-gasoline.

The results for the LCA are shown in Table 3. Consequently, two-thirds of carbon dioxide, and 90% of SO_x and NO_x can be reduced by the introduction of the electric scooter.

Table 2
Prerequisite for life cycle assessment

Vehicle	
Electric scooter (Li battery)	ICE scooter (50 ml engine)
One charge mileage: 32 km Cycle life: 500 cycles Total mileage: 16,000 km	Average fuel economy: 63 km dm^{-3} Total mileage: 16,000 km Gasoline consumption: 16,000 km/(63 km dm^{-3}) = 245 dm^3
Charge energy: 26 V × 14 Ah × 500 times Charge efficiency: 85%	

Drive speed: 30 km h^{-1}.

4. HEV battery

Table 4 shows the comparison of the HEV cell specifications between that developed in 2000 called Gen 1 and that developed recently called Gen 2. These two cells have the same dimensions and the same mass; however the capacity and power density of Gen 2 are 1.5 times of those of Gen 1. The big improvement shown in the table is supported by the some innovation of the positive electrode material and the electrolytic solution. Fig. 4 shows the power profile at 25 °C based on 5 s voltages. At 50% SOC, Gen 2 cell has the output

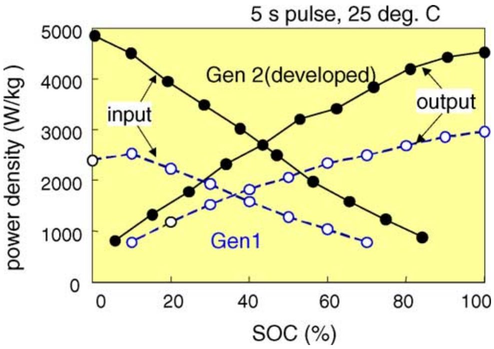


Fig. 4. Power density profile of Gen 1 and Gen 2 cell.

Table 3
Result of life cycle assessment for light vehicle battery

Vehicle	Energy consumption	Gas emission (g/veh.)		
		CO_2	SO_x	NO_x
Electric scooter (Li battery)	Li battery: manuf. to disp.	115, 172	176	100
	Total mileage (16,000 km)	82, 176	43	62
	Total	197, 348	219	162
ICE scooter (50 ml engine)	Driven by gasoline (16,000 km)	599,186	1778	2083
Reduction rate of emission by electric scooter (%)		67	88	92

Table 4
High power Li ion cell: Gen 1 and Gen 2

Item	Gen 1	Gen 2
Dimensions (mm)	Ø 40 × 108	Ø 40 × 108
Mass (g)	300	300
Nominal voltage (V)	3.6	3.6
Capacity (Ah)	3.6	5.5
Output power density (W kg^{-1})[a]	2000	3000
Input power density (W kg^{-1})[a]	1500	2200

[a] At 50% SOC and 25 °C.

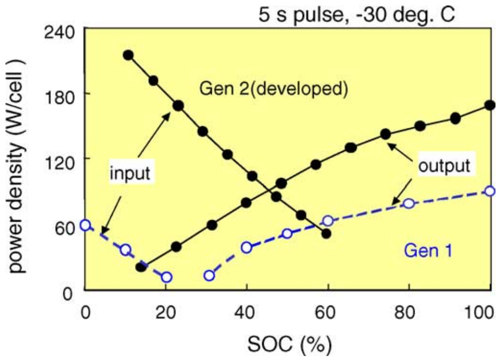
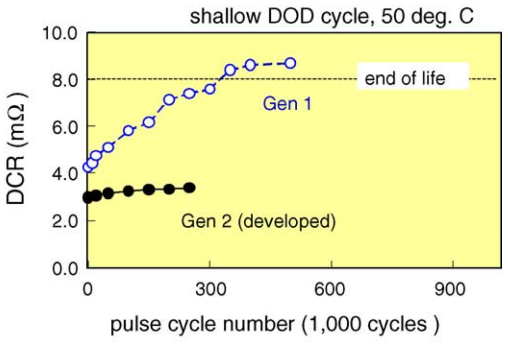


Fig. 5. Low temperature power profile at −30 °C.

power density of 3000 W kg^{-1}, and the input power density of 2200 W kg^{-1}. The power densities of the Gen 1 cell were improved throughout the whole SOC span.

Fig. 5 shows the improvement in low temperature power capability at −30 °C. The Gen 2 cell can deliver the output and input power over 50 W/cell between 25% SOC and 60% SOC even at −30 °C. The large improvement was dependent on the material innovation in the positive electrode active material and the electrolytic solution. The power profile was calculated based on the same conditions as 25 °C, namely the 5 s pulse voltage and the cut off voltage of 2.5 V. If the conditions were lowered to the shorter pulse and the lower cut off voltage, the power profile would be able to show much better values.

In Fig. 6, the DCR changes in shallow duty pulse cycle test, 1.5% for the Gen 1 cell and 1% for Gen 2 cell, at 50 °C is shown. The DCR for Gen 1 cell increased to the doubling level after 300,000 cycles, while that for the Gen 2 showed less than 10% of increment after 250,000 cycles. These results mean that the power fading in the pulse cycle test for the Gen 2 cell is much reduced comparing to that for the Gen 1 cell. Fig. 7 shows the DCR changes in the storage life test of a 50% SOC cell at 50 °C. The DCR increment for the Gen 2 cell is much less than that for the Gen 1 cell, and the DCR after 150 days storage is 3.4 mΩ, suggesting the tendency of saturation. These excellent life test data are expected to support a longer calendar life in the practical use of the Gen 2 lithium ion battery for the HEV application. Even for the Gen 1 cell, the life longer than 5 years or 100,000 km life is expected in practical application [3,6], so the calendar life more than 10 years, and may be 15 years, is expected for the Gen 2 cell based on the much suppressed DCR increase shown in Figs. 6 and 7.



* DCR : Direct Current Resistance

Fig. 6. DCR change in light duty pulse cycle test.

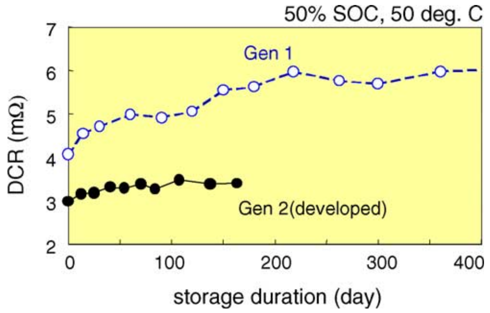


Fig. 7. DCR change in storage life test.

5. Conclusion

We have been developing Li ion batteries for industrial application, such as the automotive. Based on the last 10 years R&D results, we have developed the Gen 2 cell with high power and longer life. We expect that further application of the Li ion battery will develop in volume and variety in the near future.

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