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Short communication

Development of high-power density Li ion cell and module

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Abstract

After the development of the first version of our high-power lithium ion battery in 2000, we have been further improving its performance, such as the power and life. Our recent progress in the development on the new version (Gen 2) battery is presented. The prolonged cycle life test at 50 °C reached 900,000 cycles with a 50% increase in the direct current resistance (DCR), and the storage life test at 50 °C over 1 year showed a 20% increase in the DCR. These life test data suggested a much longer calendar life in real applications than our former lithium battery version. A new 48-cell module was developed, and it proved to have a high-power capability and good cold cranking performance as expected by the cell performance.

Keywords: Direct current resistance; Storage life; Cycle life; Cell controller; Cold cranking

1. Introduction

The lithium ion battery occupies the first place in sales volume among all kinds of batteries in Japan today, although it is still a young technology less than 20 years old. The strongest promoters for this rapid growth were camcorders, laptop computers and mobile phones. Since the market for them is approaching the saturation point in Japan, new applications such as power tools, hybrid electric vehicles (HEV) and other industrial applications like stationary use are expected to ramp up soon.

Meanwhile, we at Hitachi have been developing lithium secondary batteries since the 1980s, and in the 1990s, Hitachi continued the development of the large-sized lithium ion battery for electric power storage as a member of a national project of Japan, the Development of Dispersed-Type Battery Energy Storage Technology. We have been developing lithium ion batteries containing a manganese-based cathode material since that time [1,2].

In 2000, we launched the first version of our high-power lithium ion battery in the Nissan Tino HEV, the module for which consisted of 48 cells of 3.6 Ah–3.6 V [3–5]. After that, we have been further improving its performance, such as the power and life. We recently developed a new cell version with advanced performance, which we called Gen 2 to distinguish it from the former Gen 1. Table 1 shows the comparison between them. The capacity and power density for Gen 2 have been increased up to 1.5 times those for Gen 1. Some cell performance and initial life test data have already been reported in our previous paper [6].

We now report our recent progress in the high-power density lithium battery development, based on further cell test data, such as the life test data for our Gen 2 cell, and the 48-cell module data.

2. Experimental

The cell chemistry of the lithium battery consisted of manganese-based material positive electrode and hard carbon negative electrode. Not only the active materials but also the other materials used in our lithium ion cell were identical to those described in the previous paper [6]. Both the positive and negative electrodes were formed by coating the relevant material mixed slurry on a metal foil substrate, i.e., aluminum for the positive electrode and copper for the negative electrode. The electrolytic solution consisted of lithium hexafluorophosphate and a mixture of organic carbonate solvents. The separator was an ordinary polyolefin microporous sheet.

The positive electrode, the separator and the negative electrode were wound into an electrode assembly to form a cylindrical cell. This assembly was put into a nickel-plated steel can, and crimped with the gasket and the cap after injection of the electrolytic solution. The dimensions for the cell are 40 mm in diameter and 108 mm in length, and the designed capacity was 5.5 Ah as shown in Table 1.

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Table 1
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})	2000	3000
Input power density (W kg^{-1})	1500	2200

The rated capacity for the cell was measured at 25 °C by a discharge current of 5.5 A down to 2.7 V after the constant current–constant voltage (CC–CV) charging at 5.5 A constant current up to 4.1 V of constant voltage for a total time of 2.5 h. We determined the power profile, or state of charge (SOC)-input/output power diagram, to evaluate the power capability of the high-power density cell and module. This method is a kind of extrapolation of the *I–V* curves as precisely described in the previous paper [6].

We calculated a direct current resistance (DCR) using the slope of an *I–V* curve obtained by the constant current charges or discharges for 5 s as already described [6]. DCR is considered to be in the reciprocal relationship to the output or the input power, therefore, it will be a good yardstick to estimate the power fading of the battery.

The pulse cycle test is a simplified test to simulate the real load pattern of an HEV, and the results can be used to predict the HEV battery life affected by the stress of the repeated charge/discharge cycles during vehicle operation. We used a rather shallow duty cycle mode of 1% SOC/cycle.

The cold cranking test was intended to start cars at a very low temperature, e.g., −30 °C. We adopted the test condition proposed in the FreedomCAR Battery Test Manual [7].

3. Results

3.1. Cell performance

Figs. 1 and 2 show the basic performance of the Gen 2 cells. Fig. 1 indicates a high rate discharge capability. It shows a rather small discharge capacity loss up to 100 A (18 C), while a large discharge capacity loss was observed at 165 A (30 C). However,

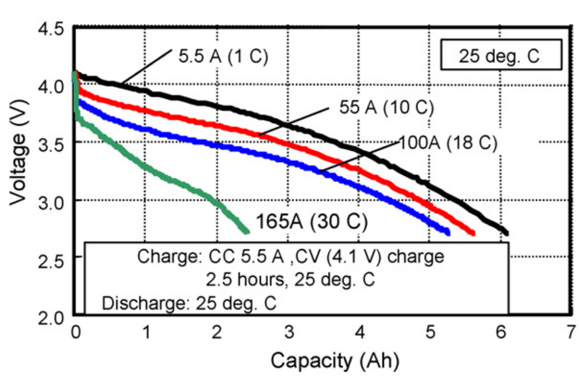

Fig. 1. Cell performance: high rate discharge capability.

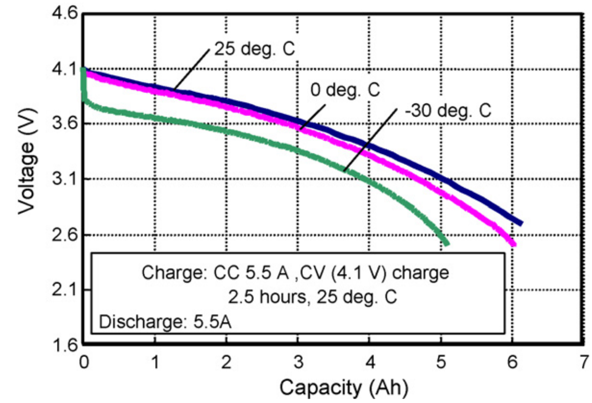

Fig. 2. Cell performance: discharge capacity.

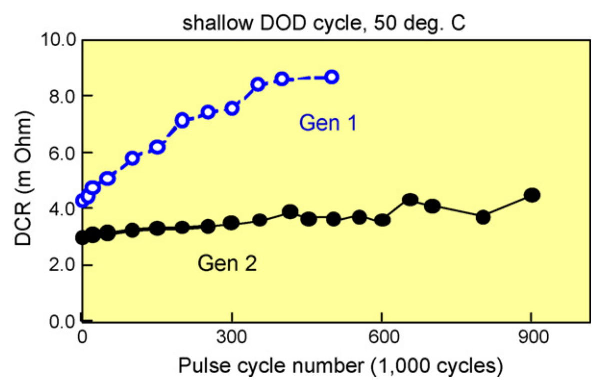

Fig. 3. Cycle life test @ 50 °C.

the pulsative discharge still showed a good performance even at this high rate. Fig. 2 is the temperature dependency of the discharge capacity at 5.5 A (1 C). Even at −30 °C, the discharge capacity was maintained around 80% of the discharge capacity of that for 25 °C. The discharge capacity change at temperatures higher than 25 °C was small.

The cycle life test and storage life test were implemented to predict the calendar life for real applications. The cycle life test result is shown in Fig. 3, and the storage life test result is shown in Fig. 4. The cycle life test at 50 °C and 1% SOC/cycle reached 900,000 cycles, and the DCR was still slowly increasing, although the change remained around 50% as shown in Fig. 3.

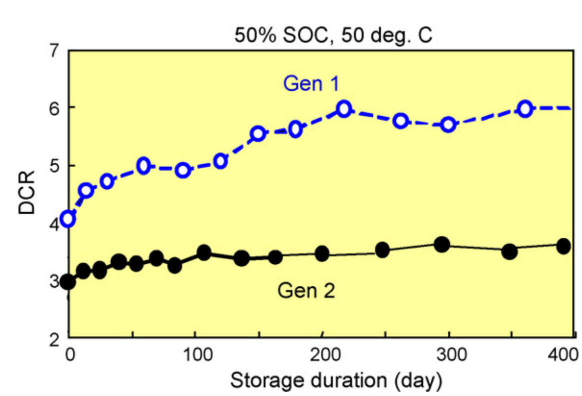

Fig. 4. Storage life test @ 50% SOC and 50 °C.

The storage life data over 1 year at 50 °C at 50% SOC is shown in Fig. 4. The DCR increment after 397 day storage was around 20%, suggesting the tendency of saturation. The Gen 2 cell test data for the cycle life and storage life in Figs. 3 and 4 are succeeding test results preliminarily reported in the previous paper [6], and are enough to convince us that what we expected at the early stage of the test was proved, and they also showed a much lower change in the DCR than the Gen 1 cells under the 50 °C environment, implying a much longer calendar life for real HEV applications.

We conducted cell abuse tests for overcharge, external short circuit, nail penetration and crush. The test conditions are based on FreedomCAR Abuse Test Manual [8]. External short circuit, and nail penetration test caused venting and small amount of solvent mist, while overcharge and crush test showed no change in appearance. Consequently, all the four tests showed no fire and no rupture. It is concluded that our Gen 2 cell still shows almost same behavior as our Gen 1 cell in abuse tests in spite of the increased energy and power in it.

3.2. Module performance

The appearance of the Gen 2 module along with the specifications is shown in Fig. 5. It consists of 48 cells connected in series, a power line harness connecting all the cells, supporting parts to form the internal structure fixing the cell arrangement, a cell controller board which uses the newly developed Application Specific Integrated Circuit (ASIC) [9], a fuse, and the module case made of steel. The dimensions, mass, and ratings are also shown in Fig. 5.

The output and input power profile at 25 °C are shown in Figs. 6 and 7. Fig. 6 shows the output power curves based on 2, 5 and 10 s discharges with the limiting condition of 120 V and 200 A. Although the longer the discharge duration, the lower the discharge power becomes, the module can supply more than 20 kW over a 30% SOC for 10 s or less. Fig. 7 shows the input power curves based on the 2, 5 and 10 s charges with the limiting condition of 201.6 V and 200 A. Although the longer the charge duration, the lower the input power becomes, the module can receive more than 20 kW under a 70% SOC for 10 s or less. According to the two figures, the Gen 2 module can supply and receive a 20 kW power for 10 s or less between 30 and 70% SOC. This high-power capability in wide SOC window means that it can support good fuel economy in HEV application.

The cold cranking test result for the Gen 2 module is shown in Fig. 8. The test conditions specified in the FreedomCAR Battery Test Manual [7] prescribes three 12-s load patterns consisting of a 2 s discharge of 5 kW followed by 10 s rest at −30 °C. Our Gen 2 module was designed to form a standard 300 V HEV battery pack with two of them. Therefore, we drew a 2.5 kW output from the module during the test. Fig. 8 shows 10-time

Fig. 5. The 48-cell module (standard design). Dimensions: 318 mm × 611 mm × 103 mm; mass: 22.5 kg.

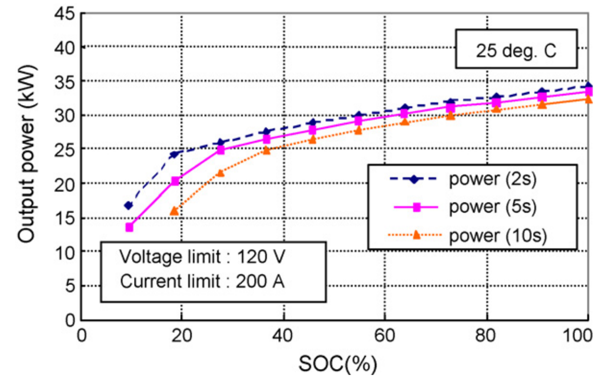

Fig. 6. Output power for Gen 2 module.

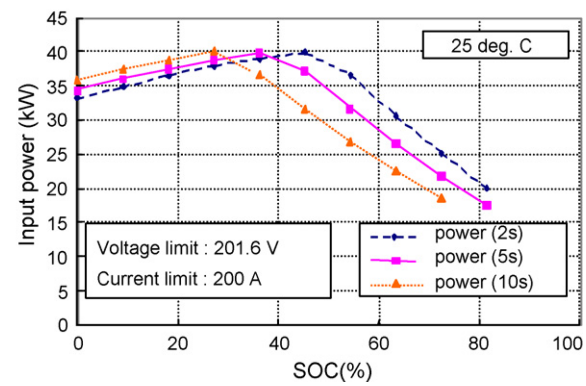

Fig. 7. Input power for Gen 2 module.

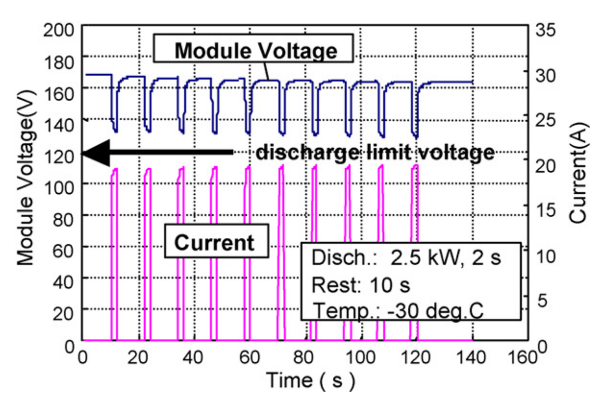

Fig. 8. Cold cranking @ 40% SOC for 48-cell module.

Table 2
Specifications of 48-cell module

	Gen 1	Gen 2
Rating (V–Ah, Wh)	170–3.6, 600	170–5.5, 900
Mass (kg)	20	22.5
Volume (dm^3)	22.5	20
#Power density ($W\,kg^{-1}$)	1350	1900
#Power density ($W\,dm^{-3}$)	1200	2100

@ 50% SOC for 5 s discharge.

iteration of the pulses at a constant wattage discharge, and the module voltage remained over the discharge limit voltage 120 V, i.e., 2.5 V $cell^{-1}$, during the iterations. This good cold cranking performance was as expected by the low temperature cell performance at −30 °C described in the previous paper [6].

Table 2 shows a comparison of the specifications for a Gen 1 module and a Gen 2 module. Both modules consist of 48 cells, cell controller boards, fuse, etc. The significant changes from the Gen 1 module to the Gen 2 module are as follows:

(1) The height is reduced to 103 mm.
(2) The module case material was changed from a polymer (FRP) to metal.
(3) The cell controller is significantly improved by the development of ASIC.

The volume is reduced by 10%, while the weight increased by 10%. In spite of the weight increase, the specific power density was increased to 1.5 times that of Gen 1, the same as the specific power density for the cell. The reason why the output power in Table 2 is different from that indicated in Fig. 6 is caused by the limiting current condition applied to the data for Fig. 6, while the data in Table 2 is just extrapolated values without a current limit. In other words, Fig. 6 shows the powers for the specified module design with definite conditions, such as harness resistance and cooling conditions. Table 2, on the other hand, just shows the power capability for the module without any limiting conditions. Nonetheless, for this difference, the high-power capability of Gen 2 module is sufficiently proved as suggested by the cell performance.

4. Conclusion

We have developed our standard Gen 2 module for HEV applications consisting of 48 Gen 2 cells. A battery with a high-power and longer life was developed on the basis of R&D for more than 10 years. We are convinced that the introduction of a high-power lithium ion battery for HEV applications will surely open the door for the further introduction of large- and medium-sized lithium ion batteries into other various applications.

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