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Idling-stop vehicle road tests of advanced valve-regulated lead-acid (VRLA) battery

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Abstract

The results of road tests on valve-regulated lead-acid (VRLA) batteries in an idling-stop (stop and go) vehicle are reported. Idling-stop systems are simple systems to improve fuel economy of automobiles. They are expected to spread widely from an environmental perspective. Performances of a conventional flooded battery, a conventional VRLA battery, and an improved VRLA battery were compared in road tests with an idling-stop vehicle. It was found that the improved VRLA battery was suited to idling-stop applications because it had a smaller capacity loss than the conventional flooded battery during partial-state-of-charge (PSoC) operation. The positive grid was corroded in layers, unlike the usual grain boundary corrosion of SLI battery grid. It is because the corrosion proceeded mainly under PSoC conditions. The corrosion rate could be controlled by potential control of positive plates.

Keywords: VRLA; Idling stop; Service life; Road test

1. Introduction

Major changes have come to automotive systems in recent years, and it is not overstated to call it the second industrial revolution for motor vehicles. This new wave includes the system transition to hybrid vehicles, 42 V mild hybrid systems, and idling-stop systems, and also includes X-by-wire systems and fuel cell vehicles.

Secondary batteries are the key for all these next-generation automotive systems. For example, the commercialized hybrid vehicles are equipped with two types of batteries. One type is Ni-MH battery for the power train, and the other is lead-acid battery for auxiliaries control.

Idling-stop systems, which shut down the engine when a vehicle is stopped, are the simplest way to improve fuel efficiency. There is a growing need for these systems in Japan to cut automobile exhaust emissions and to improve fuel efficiency [1]. These systems have been first developed for delivery trucks and buses to shut down their engines when parked or stopped, but recently efforts are being directed to passenger cars when they are stopped for relatively short time periods at traffic signals or in congested traffic.

Lead-acid batteries are likely candidates for these applications because wide spread will require low cost. Lead-acid batteries offer the best cost/performance ratios of all batteries, and for this very reason they have been used to supply automobile cranking power for over a half century. Lead-acid batteries have a wider operating temperature range than other batteries. Conventional flooded batteries have been used without any special temperature control under the harsh conditions of automotive applications, from below freezing point to near boiling temperatures.

Features of VRLA batteries are that they do not need water replenishment unlike flooded batteries, and that there are few limitations on their installation orientation. Fluid electrolyte is eliminated by absorbing and retaining the sulfuric acid electrolyte in nonwoven micro-glass fiber mat separator. Batteries can be closed because oxygen gas evolved from water decomposition on the positive electrode surface during charging is reduced to water on negative electrode surface. Plate packs of battery are closed with safety valve that keeps internal pressure below a certain level by releasing pressure when it rises. Therefore, they are called “valve-regulated” type.

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The engine stops when an idling-stop vehicle is stopped, and batteries must cover the entire electrical load in the vehicle during that time, and they must be capable of quick restoration charging during the engine is on. Batteries are discharged more frequently in these vehicles than conventional automobiles and the batteries are used in a partial state of charge (PSoC) more often [2,3]. Therefore, even if a battery has not deteriorated, it might not be able to restart the engine at a low state of charge. Batteries are expected to have plenty of endurance even under PSoC conditions. We used an idling-stop vehicle to determine how well lead-acid batteries perform.

2. Lead-acid batteries for idling-stop applications

Vehicle road tests have been conducted to develop a battery suited for idling-stop systems. Three types of lead-acid batteries were examined: a flooded battery presently used for most automotive applications; a VRLA battery mainly used for backup; and an improved VRLA battery. These batteries were installed in the auto-idling-stop vehicle and were evaluated under various conditions. The improved VRLA type incorporated the technologies of the 36 V VRLA battery for mild hybrid applications.

2.1. Improved VRLA battery

Hybrid-vehicle batteries are used in a partial state of charge to accept the regenerated power efficiently, but even under these conditions they are expected to supply high power and to be highly reliable. The main technical elements of this improved VRLA battery are as follows.

(1) *Positive plates*: Active material of even higher density than is used in conventional cycling applications was employed to decrease the active material deterioration. Usually, use of high-density active mass decreases active material utilization, but the use of new additives improved utilization for high-current discharges [4,5].
(2) *Negative plates*: High-density active material with plenty of carbon was used to prevent sulfation in PSoC use. The carbon particles form a conductive network with lead in the active material and suppress the formation of large lead sulfate particles, which acts as an insulator [5–8]. Because automotive applications require tolerance to high temperatures, the negative active material additive was optimized to improve the activity of reaction sites on negative plates and the acceptance of regenerative charge.

2.2. Experimental

2.2.1. Relationship between alternator voltage and battery SoC

Idling-stop vehicles frequently discharge their batteries that could therefore become undercharged during vehicle operation. Road tests at different alternator voltages were conducted to determine the charging voltage needed for SoC maintenance and to investigate the effects of battery differences.

Test vehicle: The test vehicle was a gasoline-powered car with 1.1-L displacement and a continuously variable transmission (CVT), modified to idle-stop automatically. The idling-stop system stops the engine when speed is 0 km h^{-1}, and automatically starts it with an ordinary starter when the driver depresses the accelerator. The CVT ensures that the car will not accelerate suddenly. Alternator voltage was continuously variable to set battery charge conditions. Maximum battery load to start engine was 500 A, and the engine started in about 0.7 s.

(1) Test batteries
(A) Conventional flooded automotive battery
(B) Conventional VRLA automotive battery
(C) Improved VRLA battery with hybrid technology
Capacity: 27 Ah/5 h rate. (Note: Each battery has the same capacity.)
The positive grid of each battery was made of Pb–0.06%Ca–1.4%Sn alloy. The negative grid was conventional Pb–Ca–Sn alloy.
(2) Test description:
Alternator voltage settings (battery voltage): 15.0, 14.4, 13.8 and 13.2 V;
Test period: 1 week;
Test course: commuting road, 15 km one way, 10 times a week (in the morning and in the evening on weekdays). The vehicle was parked during the rest of time.

2.2.2. SoC after 2 months driving

The same vehicle was used under the following conditions to study battery behavior during relatively long-term road testing.

(1) Test batteries:
(A) Conventional flooded automotive battery
(C) Improved VRLA battery with hybrid technology
(2) Test description:
Alternator voltage settings (battery voltage):
Battery A: 13.4 V;
Battery C: 13.2 V;
(Note: Based on the results of Section 2.3.2, the battery voltages were chosen to keep the batteries at the same SoC.)
Test period: 2 months.
Test course: the same profile as the test in Section 2.2.1.

2.2.3. Battery life test

The same vehicle was used under the following conditions to study battery life during long-term road testing.

(1) Test battery:
(C) Improved VRLA battery with hybrid technology
(2) Test description:
Alternator voltage settings (battery voltage): 14.0 V.
(Note: Based on the results of Section 2.3.2, the voltage was chosen to keep the SoC high at as low charging voltage as possible.)
Test period: 3 years.

Test course: Road around city area, 15 km par round, 15 times a week (three times in the daytime on weekdays). The vehicle was parked during the rest of time. It was almost the same profile as the test in Section 2.2.1.

The average temperature of Kyoto area is as follows.

The monthly mean daily maximum temperature is 35 °C in summer and 8 °C in winter.

The monthly mean daily minimum temperature is 24 °C in summer and 1 °C in winter.

The annual mean temperature is 16 °C.

2.3. Results and discussion

2.3.1. Driving pattern example

Fig. 1 shows examples of vehicle speed, engine revolutions, battery voltage, and battery current. When vehicle speed was $0\,km\,h^{-1}$ idling-stop kicked in and the engine stopped. The battery was discharged and voltage gradually dropped. Large current flowed at the next engine ignition, and there was charging current when the engine started. In this instance alternator voltage was held at 13.2 V.

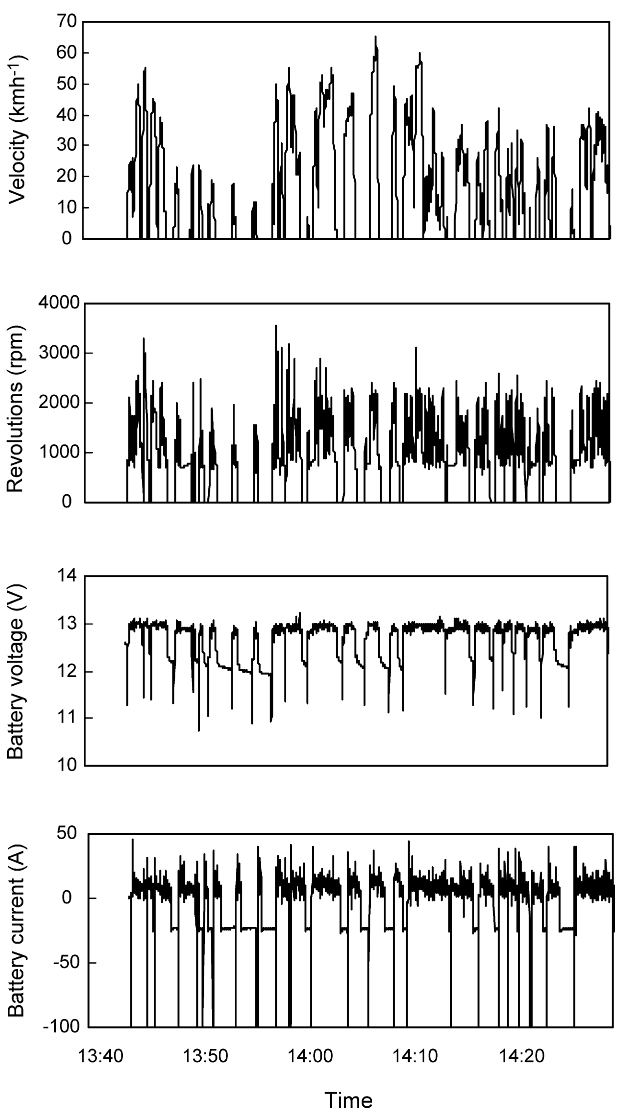

Fig. 1. Example of commuter driving data with idling stops.

Table 1

Frequency and duration time of idling stops and the average discharge current of the lead-acid battery during the full driving course

Items	From office	To office	Full-day total
Driving time (min)	67	73	140
Driving distance (km)	15	15	30
Average discharge current (A)	29	16	22
Number of idling stops (times)	22	16	38
Accumulated idling stop duration (min)	13.7	21.5	35.2
Idling stops per kilometer (times)	1.5	1.1	1.3
Idling stops per minute (times)	0.33	0.22	0.27
Total idling-stop rate[a] (%)	20.5	29.5	25.1

[a] Accumulated idling-stop duration time/driving time.

Table 1 presents the analysis results of idling-stop frequency and the average discharge current. The return-trip average discharge current was 29 or 13 A higher than when going to the office, which was because headlights were used only on the return trip while the blower fan was always on. Idling-stop frequency was 1.1 times per kilometer to the office and 1.5 from the office, accounting for 29.5 and 20.5% of driving time, respectively.

2.3.2. Relationship between alternator voltage and SoC (after 1 week of driving)

Fig. 2 shows the battery SoC after 1 week of road test. All batteries maintained 100% SoC at a charging voltage of at least 14.4 V, while the SoC dropped below that voltage. When the voltage was set at 13.2 V, the SoC was 76% in the flooded battery and 79% in the VRLA battery. By contrast, the SoC of the improved VRLA battery tended to be high at 88%. This improved battery's SoC declines only a little even at a low charging voltage.

2.3.3. Road test results (after 2 months of driving)

Road test was conducted at a low alternator voltage setting with a flooded battery and improved VRLA battery to accelerate undercharge. Voltages were chosen for batteries of different types to keep the same SoC, with reference to the results in Fig. 2. They were 13.4 V for the flooded battery, and 13.2 V for

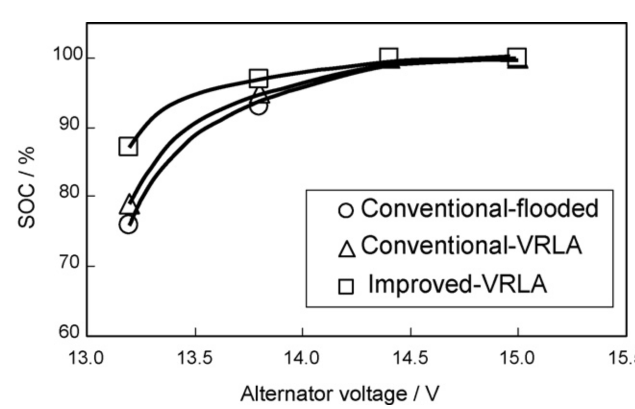

Fig. 2. Effect of alternator voltage on remaining SoC after 1-week road test.

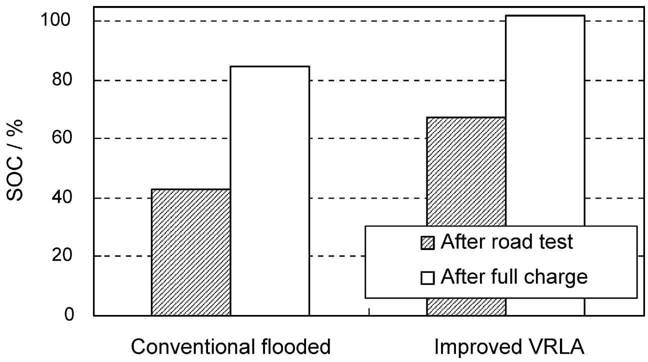

Fig. 3. Remaining SoC of conventional flooded battery and improved VRLA battery after 2-month road test.

the VRLA battery. Batteries were removed after 2 months of road test, their capacities were measured, and they were disassembled for study.

(1) *Residual capacity*: The capacities of both batteries were measured before and after full charge. Results are shown in Fig. 3. Residual capacity without charge after the road test was 43% in the flooded battery, while 67% in the improved VRLA battery. Even after full charge, the flooded battery recovered to only 85%, but the improved VRLA battery recovered to 102%.
(2) *Disassembly results*: No positive grid corrosion was found at all in either battery, probably because low-SoC use presented little opportunity for exposure to the high voltages that induce grid corrosion. Fig. 4 graphs the results of analysis for lead sulfate in the positive and negative active material of the flooded battery. Positive active material had softened at the plate tops in this battery. It is because the charge and discharge reactions concentrated near the top of the plates. The reason of this phenomenon is that continuous use in a discharged state caused lead sulfate accumulation at the bottom, and then charge and discharge reactions were hindered at the bottom. Full charging eliminated almost all the lead sulfate in the positive plates, while that at the bottom of the negative plates could not be eliminated. Fig. 5 shows the lead sulfate analysis results for the improved VRLA battery. Although there was a lead sulfate accumulation of about 20% in both the positive and negative plates just after road test had been concluded, there was no large difference between the top and the bottom as in the flooded battery, and no positive plate softening. The lead sulfate was eliminated after full charge.

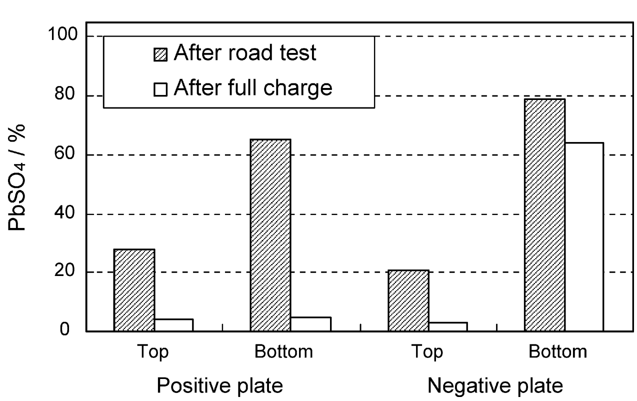

Fig. 4. Accumulated $PbSO_4$ in plates of conventional flooded battery after 2-month road test and after full charge.

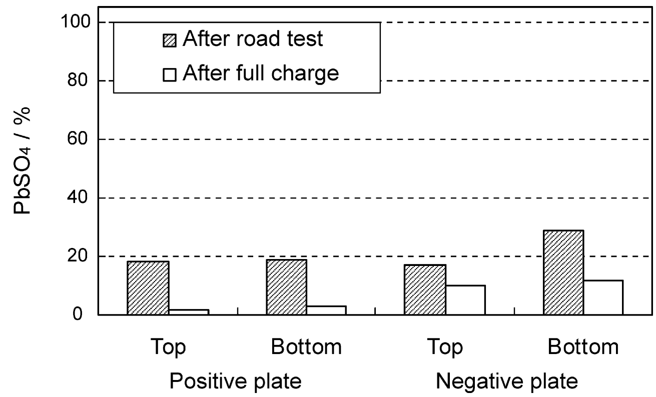

Fig. 5. Accumulated $PbSO_4$ in plates of improved VRLA battery after 2-month road test and after full charge.

2.3.4. Road test results (after 3 years of driving)

Road test with an improved VRLA battery was conducted for 3 years. Alternator voltage of 14.0 V was chosen to keep the SoC high at as low charging voltage as possible, with reference to the results in Fig. 2. Battery was removed every 6 months and tested for capacity after full charge, and disassembled for study after 3 years, 32,000 km of road test.

(1) *Capacity change*: Results appear in Fig. 6. The capacity was 70% after the 3-year road test.
(2) *Disassembly results*: Positive active material had softened without the bottom of plates in this battery. It is because continuous use in a discharged state for a long time caused lead sulfate accumulation at the bottom, then charge and discharge reactions were hindered at the bottom and the charge and discharge reactions concentrated near the top of the plates. Fig. 7 shows the cross-section of positive grid before and after the road test. Positive grid corrosion was observed, but that was not grain boundary corrosion as is usually observed in the deteriorated conventional SLI battery [9,10]. The grid was corroded in layers, and surface of

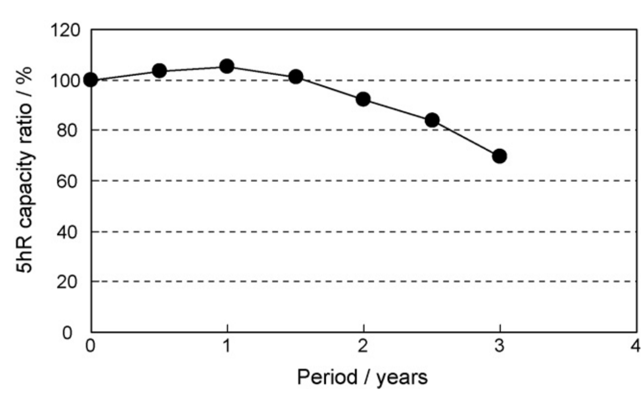

Fig. 6. Change in the battery capacity during the idling-stop road test.

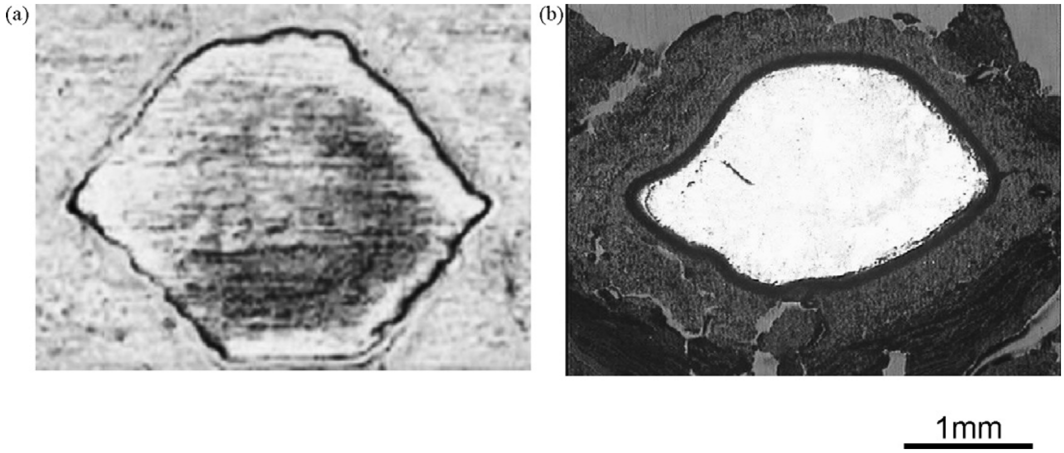

Fig. 7. Photographs of cross-section of positive plates (cast grid); (a) before and (b) after the 3-year road test.

grid on corrosion layer was smooth. It is probably because low-SoC use presented little opportunity for exposure to the high voltages that induce grain boundary grid corrosion.

2.3.5. Discussion

The results of this test suggest that the following kind of management for the lead-acid batteries in idling-stop vehicles will improve battery endurance further.

(1) *Using PSoC condition*: Positive grid corrosion can be limited with controlled overcharge.
(2) *Periodical equalizing charge*: Excessive undercharge can be limited by periodically charging to eliminate the accumulated lead sulfate. The improved VRLA battery can maintain a higher SoC than flooded batteries or conventional VRLA even at a low voltage setting.

In the next section, corrosion characteristics of positive grid were investigated to know how to control corrosion rate.

3. Corrosion characteristics of Pb alloy under idling-stop operation

3.1. Positive grid corrosion

Corrosion morphology of positive grid is generally grain boundary attack, but the positive grid of the battery on the idling-stop vehicle corroded in layers. Therefore, constant potential corrosion test was conducted to observe the corrosion morphology of grids at various potential on the positive electrode. And potential step corrosion test was conducted to compare the corrosion rate under different potential conditions.

3.2. Experimental

3.2.1. Constant potential corrosion test

Ordinary three-electrode cells were prepared for the test.

(1) Test cells:
    Working electrode: Pb–0.06%Ca–1.4%Sn alloy cast sheet;
    Counter electrode: Pb sheet;
    Reference electrode: $Pb/PbSO_4$ (5.26 M H_2SO_4 aqueous solution);
    The potential described below is based on this electrode.
    Electrolyte: 4.50 M H_2SO_4 aqueous solution.
(2) Test description:
    Potential settings: 2.02, 2.12, 2.22, and 2.32 V;
    The equilibrium potential of $PbSO_4/PbO_2$ (5.26 M H_2SO_4 aq) is 2.12 V.
    Temperature: 90 °C;
    Test period: 2 weeks;
    The cross-section of test electrode was observed after the test.

3.2.2. Potential step corrosion test

Ordinary three-electrode cells were prepared for the test.

(1) Test cells:
    Working electrode: 20 mm × 5 mm × 2 mm Pb–0.06%Ca–1.4%Sn alloy cast sheet;
    Counter electrode: Pb sheet;
    Reference electrode: $Pb/PbSO_4$ (5.26 M H_2SO_4 aqueous solution);
    Electrolyte: 3.94 M H_2SO_4 aqueous solution.
(2) Test description:
    Potential step pattern: to repeat 10,000 cycles keeping 50 s at anodic potential and 10 s at cathodic potential;
    Anodic potential: 2.24 and 2.30 V;
    Cathodic potential: 1.70, 1.80, 1.90, 1.95, 2.00, and 2.05 V;
    Temperature: 40 °C.
    The mass loss of test electrode was measured after the test.

3.3. Results and discussion

3.3.1. Constant potential corrosion test results

Fig. 8 shows the cross-section of the Pb alloy cast sheet and corrosion layer after the constant potential corrosion test. The

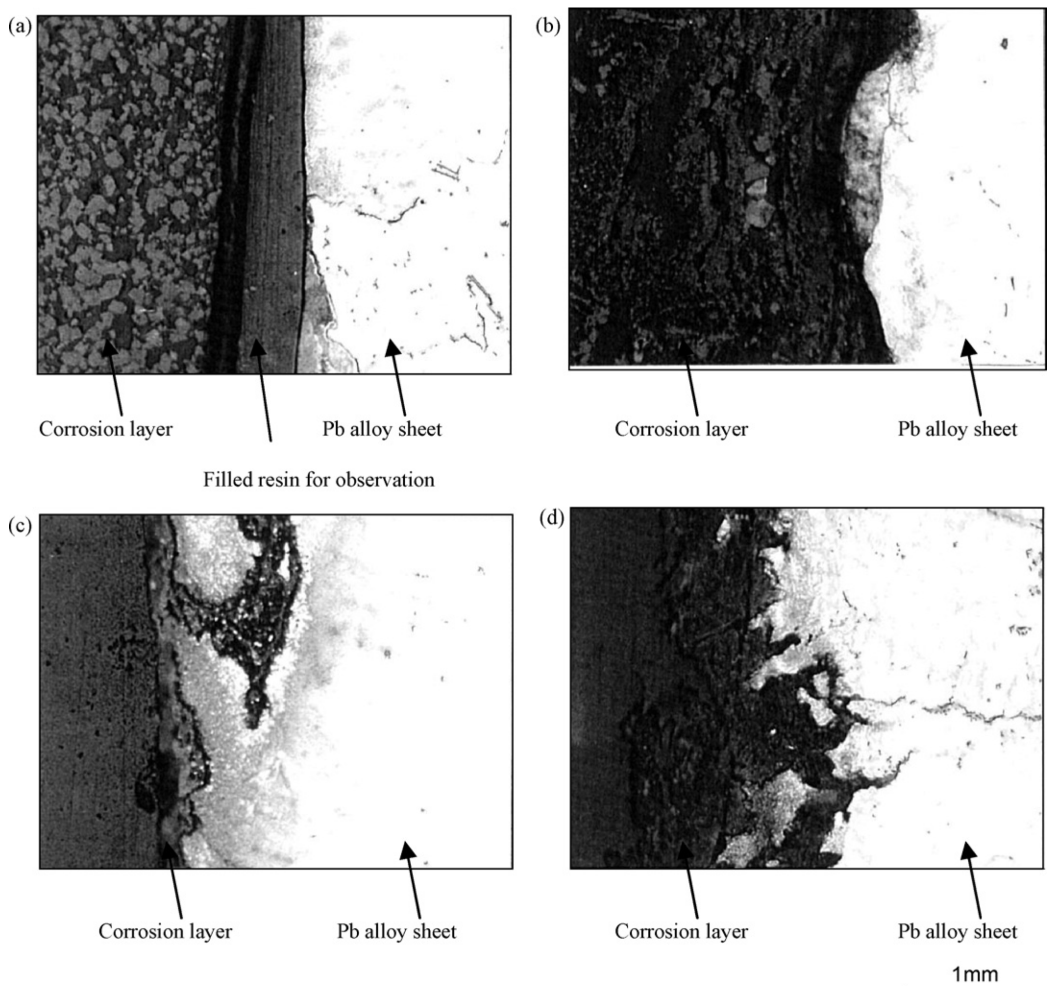

Fig. 8. Photographs of Pb alloy cast sheet after constant potential corrosion test at; (a) 2.02, (b) 2.12, (c) 2.22, and (d) 2.32 V vs. $Pb/PbSO_4$ (5.26 M H_2SO_4 aq).

electrode corroded along grain boundary at more positive potential than equilibrium potential (Fig. 8(c and d)), while it corroded in layers at less positive potential (Fig. 8(a and b)). It is ascertained that grain boundary corrosion can be suppressed under the equilibrium potential of $PbSO_4/PbO_2$.

3.3.2. Potential step corrosion test results

Fig. 9 shows the cross-section of the Pb alloy sheet and corrosion layer after the potential step test of anodic potential 2.30 V and cathodic potential 1.90 V. The electrode corroded in layers. Fig. 10 shows the mass loss of test electrode during step

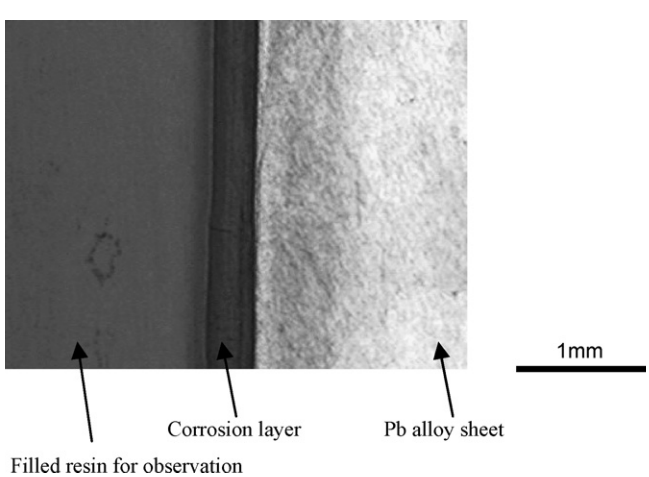

Fig. 9. Photographs of cross-section of Pb alloy cast sheet after the potential step corrosion test; anodic potential 2.30 V, cathodic potential 1.90 V.

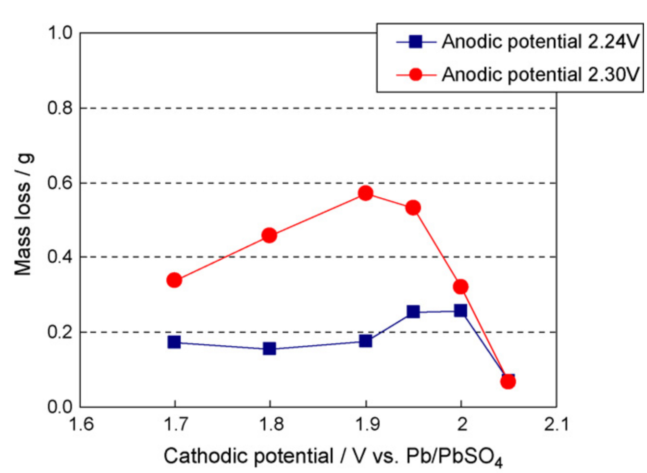

Fig. 10. Relationships between mass loss of Pb alloy cast sheet after the potential step corrosion test and cathodic potential during the cycles.

tests at various anodic and cathodic potential. Corrosion rate is higher when the anodic potential becomes more positive, and it becomes the maximums at 1.90–1.95 V cathodic potential. It is found out that corrosion can be suppressed with less positive anodic potential and preventing cathodic potential from 1.90 to 1.95 V during cycles.

3.3.3. Discussion

Grain boundary corrosion of positive grid can be suppressed under PSoC conditions of batteries, because the positive grid potential tend to be under the equilibrium potential of $PbSO_4/PbO_2$. The positive grid corrodes in layers, so the service lifetime of grid will become longer for the same corrosion rate.

It was effective to suppress the positive grid corrosion by controlling the anodic and cathodic potential during the PSoC cycles. Therefore, it may be also effective for batteries in idling-stop vehicles to be charged at lower voltage or to be designed with larger size.

4. Conclusion

This paper has described an example of lead-acid battery performance in an idling-stop application. The improved VRLA battery, enhanced through use in a 42 V mild hybrid vehicle, performs excellently in idling-stop applications.

The results suggest that the following kind of the lead-acid batteries and their management in idling-stop vehicles will improve battery endurance further.

(1) Large size batteries.
(2) Using PSoC conditions with lower charging voltage.
(3) Periodical equalizing charge.

The success of idling-stop systems depends greatly on a combination of battery management and the improved VRLA battery.

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