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Short communication

The optimisation of grid designs for valve-regulated lead/acid batteries for hybrid electric vehicle applications

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ABSTRACT

The design, construction and testing of valve-regulated lead/acid cells with grid designs optimised for high-rate partial state-of-charge cycling for hybrid electric vehicles are described. Computer modelling was used to develop the grid designs. This showed that designs with opposed tabs and terminals on the top and bottom of the cell were likely to have the best performance not only in terms of grid conductivity but also for uniformity of active material utilisation. Prototype cells were built and tested. Low rate performance was in line with the designs and the high-rate performance was substantially enhanced compared with conventional constructions. The cells were then tested to a shallow cycling regime and to a simplified hybrid electric vehicle cycle. The results showed excellent life under these conditions without the benefit of carbon or graphite additives to the negative active material that have also been shown to improve cycle life under these conditions.

1. Introduction

The development of valve-regulated lead/acid (VRLA) batteries for application in hybrid electric vehicles (HEVs) has been directed towards the resolution of problems arising from the need to operate the battery in a partially discharged state in order to be able to accept charge from the vehicle for energy recovery. This high-rate partial state-of-charge (HRPSoC) operation leads to problems with the negative plate [1] which loses capacity because the lead sulphate discharge product tends to agglomerate or forms within the grid in locations where it cannot be readily recharged. Intermittent charging to a full state-of-charge may partially rectify the loss of capacity but in practice this is not a good solution and ways of improving the behaviour of the negative plate are being investigated. Two main approaches have been studied: first, to improve the conductivity of the negative active material by adding carbon or graphite in larger quantities and, second, to improve the grid design with the aim of decreasing the internal resistance of the cell. In the work described in this paper, the effects of changing the grid design not only to reduce internal resistance but also to ensure that the positive and negative electrodes are operating more uniformly have been studied. The effects of conductive carbon or graphite additives have not formed part of this study in order to identify the potential of improvements in grid design alone to enhance battery performance for HEV duty cycles.

The first part of the work was a finite element simulation of grid designs aimed at improving overall battery performance. This approach has been well developed [2,3] and in this case the model was validated experimentally with two iterations of simulation were carried out in order to arrive at a preferred design. A small cell suitable for HEV applications was then designed and built using grids laser cut from extruded sections. These were parameter tested at low and high rates prior to tests under shallow cycling and in a simplified HEV regime. The results of these tests are presented below.

2. Development and validation of a finite element cell model

A finite element model was established with lead grids with blocks of electrolyte between the grids. The grids used for this had a thicker side current collector and a central part with a reduced section containing the grid members. The electrolyte was only in contact with the area of the grids with grid members and active material and a block thickness of 20 mm was used to achieve perpendicular current flow through the block to emphasis the effectiveness of the grid design. The electrical constraints were a voltage of 1.0 V at both ends of the plate lugs and 0 V at the other side of the electrolyte block. The electrical conductivity of lead was taken as $2.06 \times 10^{-7}\ \Omega\,\text{m}$ and for the block $0.02\ \Omega\,\text{m}$. The model was of the grid in contact with electrolyte only and did not consider the

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effect of the active materials as the purpose was to optimise the grid design. ANSYS 10 software was used with free-meshed quadratic tetrahedral elements having a maximum side length in the grid of 2 mm and 5 mm in the block. In the first instance, an existing grid design was used for the simulation and the results were compared with the measurements made on an actual grid. The voltage and current distributions were calculated. For the experimental set-up a grid was immersed in 5 M sulphuric acid and measurement was made at 2 kHz so that calculated and actual values could be compared. The measured values differed from the calculated values by ~5% and the sum of the deviations (positive and negative) was close to zero. Furthermore, the deviations were random rather than systematic and as a result the simulation was judged to be capable of providing a reasonable basis for comparison between grid designs.

3. Computer simulation of grid designs

The first sequence of simulations was carried out to determine which combination of grid design and cell layout relative to lug position provided the best starting point for subsequent optimisations. For each arrangement, a map of current density per unit area and voltage distribution was generated but the assessment of these becomes subjective and three parameters were measured to quantify the evaluation. These were:

(i) j_{mean}, the mean current density between the grids.
(ii) σ_j, the standard deviation of the current in the electrolyte.
(iii) ΔU_{max}, the maximum voltage drop in a grid.

Different arrangements of the side current collector were simulated: (i) with single tabs on the same side at the top, (ii) with single tabs on opposite sides at the top, (iii) with single tabs on the same side at top and bottom, (iv) with single tabs on opposite sides at top and bottom, (v) with double tabs on the same side and (vi) with double tabs on opposite sides. For these types radial and rectangular grid designs were compared. Central current collectors were simulated with single tabs at the same and opposite sides and also double tabs. The thickness of the side current collector was also varied.

Sorting the results by j_{mean} provides a measure of total cell efficiency and the double lug designs were ranked highest, followed by the double tab designs with a central current collector. The radial designs did not provide significant improvements but the designs were not optimised. Sorting the results by σ_j shows the best performance with tabs on opposite sides. In this case the cells are optimised for uniform current distribution which in turn provides optimum mass utilisation but the ranking number has two factors which need to be considered in interpreting the results. First, the standard deviation measures the absolute width of the distribution and designs with a higher current density are treated less favourably and, second, with central current collectors, there are two additional edges and, in turn, double the number of outlying values. Finally, sorting the results by ΔU_{max} shows that designs with double tabs are superior and, as above, radial designs were not especially beneficial. Overall, these data showed that designs with opposed tabs had the best performance.

Following this iteration a further simulation was carried out in each case (unless prevented by the nature of the cell design) with tabs in line, tabs vertically opposed, tabs diagonal and tabs opposite to each other as in a conventional design. The variations considered were (i) two side tabs of 15 mm width or one side tab of 25 mm width with the top section tapered away from the tabs and tapered wires, (ii) conventional tabs, (iii) varying the width of the current collector from 8 to 12 mm, (iv) adding tapered wires in 0.5 mm steps from 1.0 mm (no taper) to 2.5 mm, (v) adding more horizontal wires, (vi) radial designs with dual and single side tabs and (vii) using hexagonal pellets across the whole grid with a 1.0 mm wire and an area of 72 mm^2. These were analysed as before and the selected design had opposed single tabs and tapered wires. Similar conclusions have been reached by earlier studies [4] but have not been evaluated under an HRPSoC duty cycle. The basis of selection was both for performance and ease of manufacture.

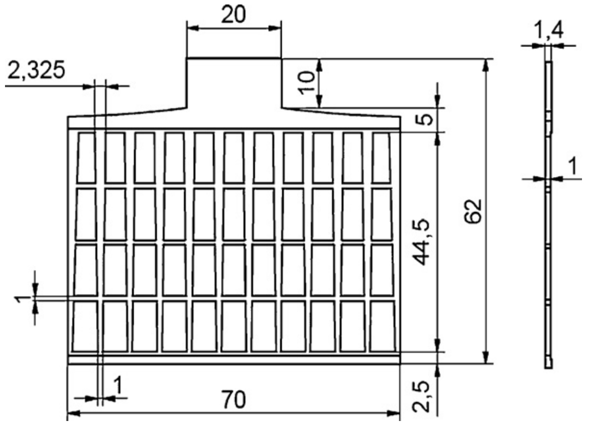

Fig. 1. Preferred positive grid design. The negative used the same design except that the overall thickness was 1.2 mm in the wider section and 0.8 mm in the centre. The grid section was extruded with a thinner section in the centre and the active material pasted flush to the thicker section. The vertical wires were tapered towards the lug and top bar increased in depth towards the lug. The plates were arranged with the negative plates opposed to the positive plates with the lugs opposite.

Fig. 2. Prototype cell. The terminals are on the top and bottom of the cell which has a closure on both sides of the cell and a Bunsen valve vent on one side only.