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Impact of separator design on battery performance in traction applications

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Abstract

The lead–acid battery continues to be the battery of choice for traction applications. Golf carts, lift-trucks and automatic guided vehicles are only a few of the traction-related markets which depend on the lead–acid battery for their continued growth and success. Throughout the world, traction battery manufacturers use a wide range of grid designs, grid alloys, paste formulations, separators and other features to optimize the deep-cycle performance of their products. In this complex array of design features, the least understood parameter is most likely the battery separator. Though somewhat inconspicuous by nature, the traction-battery separator can, if properly selected, play a key role in performance, by extending the life of both the positive and negative plates while at the same time reducing battery maintenance and power requirements for recharging. This paper discusses the various design features of a battery separator and describes how such features may be used to effect the performance and life of the traction battery. Separator porosity, material composition, backweb thickness, rib dimensions and the use of attached glass mats are some of the controlled variables. © 1999 Elsevier Science S.A. All rights reserved.

Keywords: Lead–acid battery; Separator design; Traction battery

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1. Introduction

The lead–acid battery continues to be used for the bulk of traction applications around the world. Because of its durability and relatively low cost per cycle, the battery remains the work-horse of the industry. The manufacturers of traction batteries continue to push the performance envelope by using all possible design variables. The design of the grids, plates, separators and even the containers—each play an important role in the ultimate life and performance of the battery system.

It is the overall goal of the designers of lead–acid traction cells to maximize simultaneously the performance and the life of the cell. The ultimate traction cell will have the highest discharge capacity and the highest power capabilities while offering the user the lowest maintenance and excellent cycle-life. In reality, the cell designer sacrifices discharge capacity and power somewhat in order to improve the cycle-life of the cell. All these variables are interrelated and a change in one will typically effect several others. These relationships are well understood such that, over the years, cell designs have generally been optimized for performance and life. One somewhat overlooked design variable tends to be the battery separator. In many instances, the separator is taken to be a totally inert component which is used simply to separate plates of opposite polarity while offering as little resistance as possible to ionic flow [1]. The informed cell designer recognizes that the separator, even in its simplest form, can be used to maintain the integrity of the positive plate and therefore increase cell life. Although this feature is appreciated by the cell designer, some of the other aspects of the battery separator are less well known. To bridge the gap in knowledge, this paper addresses the effects of the various design features of a traction battery separator.

2. Physical properties of separators

2.1. Material composition

The composition of the separator is a critical choice for the cell designer because it ultimately affects most of the other separator-related parameters. There are many differ-

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ent materials and technologies employed in the manufacture of battery separators. The most common types of separators used for stationary batteries are: polyethylene (PE), polyvinyl chloride (PVC), natural rubber (NR), and phenolic resins (PH). For completeness, it must also be noted that the original lead–acid battery separators were made from sheets of wood, particularly Port Orford Cedar or Douglas Fir, but despite many advantages were discontinued due to cost.

PE separators are manufactured by blending ultrahigh-molecular-weight PE pellets with a mixture of silica and oil. This mixture is then thermally extruded into a sheet and ribs are added via a calendering operation. The bulk of the oil is then extracted to produce micro pores. The remainder of the oil (10–20%) is used in the separator to improve the oxidation resistance. PE separators are very flexible and offer excellent oxidation resistance if the residual oil content is controlled [2].

Separators based on PVC are produced by combining high-molecular-weight PVC powder, silica, water, and a solvent. This mixture is extruded into a sheet at low temperature (60°C) and then calendered to produce the desired rib pattern and thickness. The solvent is extracted via hot water to produce the finished separator. The separators are rigid and have excellent oxidation resistance [3].

NR separators are manufactured from a mixture of natural rubber, silica and water. After the components are blended in a Banbury-type mixer, the mixture is extruded into a sheet. Various rib patterns are then formed on one or both sides of the sheet by means of a special calendering operation. The calendered sheet of raw separator material is then cured using either sulfur vulcanization or cross-linking via an electron beam to produce, respectively a rigid or flexible separator product. NR separators have excellent thermal stability and wettability, are free from impurities, and have been demonstrated to retard heavy metal migration (wooden separators are also known to inhibit the migration of metals such as antimony) [4,5].

PH separators are produced by blending silica with a modified phenolic resin which is formed into a sheet. This semi-solid is then calendered and thermally cured on to a polyester reinforcing web. Ribs are added in a separate step. This type of separator is strong and rigid with fairly good oxidation resistance [6].

2.2. Strength

A traction battery separator is required to have sufficient physical strength to endure the rigours of cell assembly and day-to-day charge–discharge cycling. Physical strength is required to withstand basic handling, cell blocking/assembly, physical shock, punctures, abrasion, and compression. To insert a tightly fitting cell stack into a container, the separator and ribs must be able to endure compressive forces. The possibility of a paste lump in a tightly fitting cell mandates that the separator be vibration and abrasion resistant. Though not completely representative of the overall physical strength of the battery separator, tensile strength is often used as a measurement. Typical values of tensile strength are shown in Table 1 for five different separator materials which are typically used in the traction battery industry [1].

2.3. Rigidity / flexibility / brittleness

Another aspect of separator strength is the ability of the separator to bend. If the material is too rigid, the separator tends to be brittle and its corners are easily broken during cell blocking and assembly (Table 1). The nature of separator processing, which is typically performed in strip form, tends to produce materials which are more brittle along the processing direction of the material. Too much flexibility in a separator material gives rise to other problems during assembly such as folding, creasing and wrinkling.

Table 1
Selected properties of separators

Material composition	Polyethylene	PVC	Hard rubber	Flexible rubber	Phenolic resin
Strength	Excellent	Good	Good	Fair	Good
Rigidity/flexibility/brittleness	Flexible	Rigid	Rigid	Flexible	Rigid
Mean pore diameter (μm)	0.10	0.22	0.20	0.06	0.50
Volumetric porosity (%)	55–65	60–70	50–60	45–55	60–70
Water permeability (cc psi^{-1} cm^{-2} min^{-1})	0.045	0.13	0.031	0.020	0.049
Backweb thickness (mm)	0.65	0.60	0.70	0.35	0.60
Maximum separator thickness (mm)	3.5	4.2	5.8	4.1	3.6
Electrical resistance (Ω cm^2)	0.120	0.130	0.280	0.250	0.140
Oxidation resistance	Excellent	Excellent	Very good	Good	Good
Resistance to antimony transfer	no	no	yes	yes	no
Thermal resistance	Good	Good	Excellent	Good	Good
Rib styles	V/D/S	V/D	V/S	V/S	V/D/S
Glass mat	Available	Available	Available	Available	Available

V = vertical; D = diagonal; S = serpentine.

2.4. Pore size

It is not easy to define the size of the pores in a battery separator. The nature of these porous materials results in a distribution of pore sizes rather than in one discrete size of pore. In selecting a separator material, the cell designer should certainly consider that smaller pores are more resistant to ‘leading-through’, but this does not tell the entire story. The pore-to-pore structure or paths leading from one pore to the other (i.e., the tortuosity) can be equally, if not more, important in preventing ‘leading through’ than the mean pore diameter. It must also be realized that as the mean pore-size is decreased, both the water permeability and the electrical resistance will suffer (for equivalent separator backweb thicknesses). Thus, all aspects of the cell design must be considered. The variation in the mean pore-size from material to material is illustrated in Table 1.

2.5. Volume porosity (%)

This parameter describes the ability of the separator to hold the sulfuric acid electrolyte. It is a fact that the separator takes up the space in the cell that could be better occupied by active materials such as sulfuric acid electrolyte, positive active material (PAM), and negative active material (NAM). Volume porosity describes the volumetric percentage of the separator that is void and able to contain sulfuric acid. The acid in this space is held in a ‘porous reservoir’ for use in the cell as it is being discharged. The longer the discharge, the greater is the need for acid from the reservoir for utilization in the discharge reaction. The cell designer must consider this acid volume when determining the required ratio of active materials which, in turn, defines the maximum material utilization and the limiting electrode (see Table 1).

2.6. Permeability (to water)

This property of the separator is a measure of the rate at which electrolyte can physically move through the separator. Permeability is a very practical measurement which describes the overall effect of pore size, volume porosity, tortuosity and separator backweb thickness. During discharge of a traction cell, especially at high rates, acid is rapidly depleted at the surface of the plates. The permeability of the separator (see Table 1) gives the cell designer a quantitative indication of the ability of the separator to supply acid where it is needed in the cell. The cell designer must also use this parameter to estimate the ability of the separator to transport unwanted substances such as antimony and oxygen. The higher the permeability, the higher the acid mobility, but the greater the tendency of the separator to allow antimony to reach and poison the negative plate as the positive grid corrodes. Also, highly permeable separators have shown a tendency to transport oxygen and this can result in depolarization of the negative through a recombination mechanism similar to that which occurs in a valve-regulated lead–acid cell.

2.7. Backweb thickness

The thickness of the backweb is one of the most easily controlled parameters in the design of a battery separator. The thickness is typically controlled with a calendaring operation, and can be used to alter the permeability, resistance to leading-through, electrical resistance, pinhole resistance, and the strength of the separator. Due to the nature of separator-processing technologies, the various manufacturers are able to offer a range of separator backweb thicknesses; these, of course, have a minimum and maximum based on the prescribed technology (see Table 1).

The thicker the backweb for any given separator material, the higher the strength, electrical resistance and resistance to leading-through, but the poorer the high-rate performance. The thinner the backweb, the lower the electrical resistance and the better the high-rate performance, but the greater the tendency for separator defects such as pinholes, fractures and handling problems.

2.8. Pinholes

Though it is obvious that pinholes in the separator will lead to leading-through and ultimately to electrical shorts, the subject should be briefly discussed. Pinholes tend to be a function of the manufacturing process. The battery designer must therefore work with the separator manufacturer to verify that pinholes are minimized. Thorough testing and evaluation are required by the separator manufacturer to ensure that proper processing and inspection techniques are practiced. Pinholes by their very nature can be more common in separators which have a very thin backweb.

2.9. Electrical resistance

Separator electrical resistance is a measure of the ability of the acid-filled separator to support the flow of ions. This ability to support ionic flow (ionic conductivity) is a direct measure of the ability of the separator to perform under high-current conditions. Therefore, the cell designer can use the electrical resistance values (see Table 1) to estimate directly the voltage losses which are attributable to the separator in a specific application or design. The overall design of a traction cell is not optimized for extremely high-rate discharges and, therefore, the electrical resistance of the separator does not contribute significantly to the total voltage losses in the cell.

3. Chemical properties of separators

3.1. Oxidation resistance

A battery separator must be able to withstand the oxidizing power of the lead dioxide in the PAM and the corrosive nature of sulfuric acid at temperatures as high as 75°C. While it is arguably not representative of actual battery service, the industry uses an oxidation–resistance test whereby separator samples are examined for weight loss when subjected to soaking in chromic acid (see Table 1). The greater the oxidation resistance, the longer the separator will survive in a traction cell without cracking or softening. The resistance to oxidation of PE separators can be significantly effected by the residual oil content left in the material after manufacturing. Too little oil and separator oxidation can be severe, too much and the oil may leach out, contaminate the electrolyte and, thereby, cause maintenance problems. Accurate process systems must be in place at the separator manufacturing plant to ensure proper control of the residual oil levels.

3.2. Antimony transfer

The battery separator itself can also be used to counteract the deleterious effects of trace levels of antimony that may be found in the electrolyte. Antimonial alloys, which are the key to maximizing the cycle-life of the positive plate, are known to poison the negative plate. Antimony enters the electrolyte during cycling as the positive grid corrodes. The antimony then reaches the negative plate where it ‘plates out’ and increases the rate of hydrogen evolution and decreases the negative charge-acceptance. In days past, wooden battery separators such as Port Orford Cedar or Douglas Fir were known to inhibit antimony transfer [7], but despite their advantages were discontinued due to cost and availability.

Nowadays, the problem of antimony transfer still exists and can be traced by carefully monitoring the end of charge current throughout the life of the traction cell. A study has indicated [2] that during cycling, capacity loss in traction cells coincides with the onset of a continual increase in the end of charge current. This same study has shown that NR separators possess the ability to inhibit this phenomena and extend the life of the cell. It is believed that the organic materials found in NR produce similar effects as the ‘lignin’ compounds found in wood.

3.3. Thermal resistance

As in the case of oxidation resistance, the traction battery separator must be able to withstand the rigours of thermal cycling in the battery. During charging and discharging, significant amounts of heat are generated in the cell. Heat due to ohmic losses or the thermodynamics of converting lead and lead dioxide into lead sulfate and back again can raise the cell temperature to almost 75°C. The best separators show little or no embrittlement, softening or volume change when exposed to elevated temperatures (see Table 1).

4. Additional properties of separators

4.1. Ribs / mini-ribs

Ribs and mini-ribs are the portions of the separator that extend from the backweb toward the plates. These raised portions of the separator tend to be vertical but may be diagonal or serpentine. Other rib designs have appeared from time to time such as interrupted ribs, dimples, ‘Z’ ribs, etc., but by far the most common are still vertical, diagonal or serpentine. Ribs and mini-ribs are typically used by the battery designer to: (i) minimize separator contact with the positive plate; (ii) form an acid reservoir near the positive or negative plate; (iii) permit proper gas evolution; (iv) control cell stack compression; and (v) absorb dimensional tolerances within the cell stack or element.

The strongly oxidizing nature of the positive plate makes it necessary to minimize contact with the separator. Ribs have always been used to reduce this contact to less than 10% (some separator materials have lower oxidation resistance than others, and for this reason should be carefully tested prior to use).

The ribs are also used by the cell designer to form narrow acid reservoirs between the plates. During discharge of a cell, acid is consumed and water is produced. As acid is depleted within the pores of the plates, acid is replenished via these reservoirs. Also, during recharge highly concentrated acid is generated within these same pores and would concentrate at the plate surface and slow down the recharge reaction if it were not for the use of the ribbed separator and its acid reservoirs. The ribs also permit hydrogen and oxygen to escape freely from the plates during recharge which, in turn, results in thorough mixing of the acid during overcharge. In traction cells, mini-ribs may be placed on the separator surface facing the negative to facilitate the escape of gases but also to absorb the growth of the NAM.

Finally, rib spacing (or pitch) of both the main and mini-ribs must be considered as a compromise to acid availability versus plate material and overall cell support. Since the ribs are narrow and somewhat compressible, they serve to absorb dimensional variations in the plates, both initially and during service life, so that cell stack compression can be maintained.

4.2. Glass mat

The use of glass mats as part of the lead–acid separator has proven extremely useful in improving the life of traction batteries. In practice, the glass mat is usually attached to the battery separator during the separator manufacturing process. An adhesive is applied to the tops of the ribs and the glass mat is added by means of a calendering process. It is also an accepted design variable to place the glass mat on the flat side of the separator, as dictated by which plate requires the additional support.

The main function of the glass mat is to help retain the integrity of the positive plate. Through the use of glass mats, paste shedding is greatly reduced during overcharge and deep-discharge cycling, which in turn extends battery life. Inclusion of a glass mat may cause a slight increase in the electrical resistance of the separator. In most cases, however, the added electrical resistance related to the glass mat does not impose a great impact on battery performance, except in applications which require extremely high discharge rates. The glass mat also helps to insulate the separator from the highly oxidizing PAM and, thereby, improves the oxidation resistance of the separator.

5. Summary

This paper has addressed the effects of the various design features of a traction-battery separator and has described how these features can be employed to improve cell performance and life. It is the task of cell designers to make use of this information, by addressing these issues with separator manufacturers, in attempts to improve their respective battery products.

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