Failure Mode Effects and Criticality Analysis of the manufacturing process of lead-acid battery

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***Abstract*— This paper reviews the lead acid battery performance related to the manufacturing process problem. Chemical reactions occurring during the manufacturing process of lead-acid batteries have a significant impact on their performance and lifetime. Understanding and control of these chemical and electrochemical processes will result in battery performance. In this context, the authors propose an approach to study the degradation of lead acid battery during the manufacturing process by adopting a quantitative analysis based on the Failure Mode and Effects and Criticality Analysis (FMECA). This analysis allows determining, classifying and analyzing common failures in lead acid battery manufacturing. As a result, an appropriate risk scoring of occurrence, detection and severity of failure modes and computing the Risk Priority Number (RPN) for detecting high potential failures is achieved.**

***Keywords*—lead acid battery; degradation; failure mode; critical causes;**

I. INTRODUCTION

Energy storage technologies in industrial applications play an important role in maintaining the system uptime. Lead acid batteries are among the most used devices to store and deliver energy. Indeed, the use of the lead acid batteries in these different applications causes a problem related to the limit of their lifetime. This limit of lifetime is generated either by faulty operation, or by faulty manufacturing [1,2]. In fact, it is very important to evaluate the safety and reliability of energy storage system by using tools analysis such as Failure Modes and Effects and Criticality Analysis. During the manufacture of the lead acid battery, various chemical, mechanical and metallurgical parameters have a profound impact on the composition and crystal structure of active material. The optimal composition and structure of the active mass formed in the plate manufacture are quite important to the initial capacity and the battery life [3]. In fact, the limits of their performances are generated by the qualities of the lead oxide, paste, grid, pasting, curing, drying, soaking and formation of the plate, assembly and finishing.

The main objective of this paper is to analysis the degradation of the lead acid battery during manufacture process by standardized Failure Modes and Effects and Criticality Analysis.

In this paper, the different steps of lead acid battery manufacturing are described and modelled by Structured Analysis and Design Technique (SADT). The SADT is completed by a (FMECA) Failure Mode and Effects and Criticality Analysis in order to identify the critical causes of low quality of the lead-acid battery manufacturing process. The FMECA is a powerful technique that was originally developed to improve the reliability of product. It is used to identify the failures modes, estimate the impact of the failures, determine the critical causes, and develop appropriate countermeasures to reduce or eliminate the risk of potential failures.

II. MANUFACTURING PROCESS OF THE LEAD ACID BATTERY

The major components of a lead acid battery are the two electrodes, the electrolyte and the terminals. The electrodes consist of a grid and the active material. The purpose of the grid is to distribute the current and provide mechanical support for the active material. In the manufacturing process of the lead acid battery, the plates are formed from the application of the paste on the grids lead alloy. In fact, the paste of the plates is formed by mixing the lead oxide with water, sulphuric acid and additives. The additives of the positive paste allow the improvement of the porosity, conductivity and handling of material deposited on the plate. The positive additives are diatomite, glass microspheres, expanded graphite, barium plumbate, Titanium silicide, etc. The improvement of conductivity, porosity and holding of the sponge lead on the negative plate are provided by the addition of additives such as lignosulfonate, black carbon, barium sulfate, etc.

During the curing and drying process, the plates are transported to curing chamber in order to allow the adhesion of the paste on the current collector. The curing step ensures the interconnection of the paste particles into a solid porous mass, the oxidation of free lead, the conversion of basic lead sulfate, the oxidation of the grid alloy and the formation of a corrosion layer (CL) on the grid surface to improve the adhesion between the cured paste and the grid [4,5]. The drying step provides the improvement of the quality of the plate's texture.

The process of formation can be conducted via two basic technological schemes namely, tank formation and container formation. In the tank formation, the plates are immersed in the electrolyte to ensure the soaking and formation process

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under controlled conditions of temperature, current density, humidity and time.

After the formation process, the positive plates are placed on those negative alternately to form an electrode in the assembly process. A beam of positive and negative electrodes is formed by the placing in parallel of the positive and negative electrodes. The two beams of electrodes are disposed so as to have an alternation between electrodes of different polarity spaced by micro-porous separators to ensure the electrical isolation between them. All components (positive electrode, separator and negative electrode) were inserted into a commercial housing of battery. On the last step, the battery is subjected to the finishing process [4-7]. The diagram of the lead acid battery manufacturing is shown in Fig.1.

The study of the various manufacture process of lead acid battery allows identifying and modelling, in a diagram of information flows by SADT, the making processes associated with manufacturing systems. The global model of the lead acid battery manufacturing is shown in Fig.2. It is composed of several hierarchical blocks. The A0 block is the top-level, which presents the overall system. This block is broken down into lower level in order to describe the subsystems (manufacturing of the lead oxide, manufacturing of the paste, manufacture of grid...). This lower level is composed of boxes (representing activities) connected by arrows (representing flows of materials, data, or information).

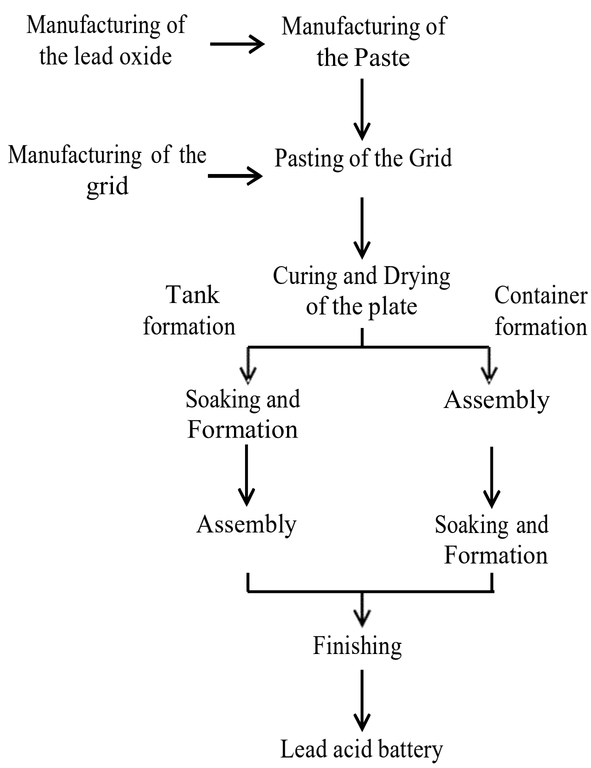

Fig. 1. Diagram of lead acid battery manufacturing

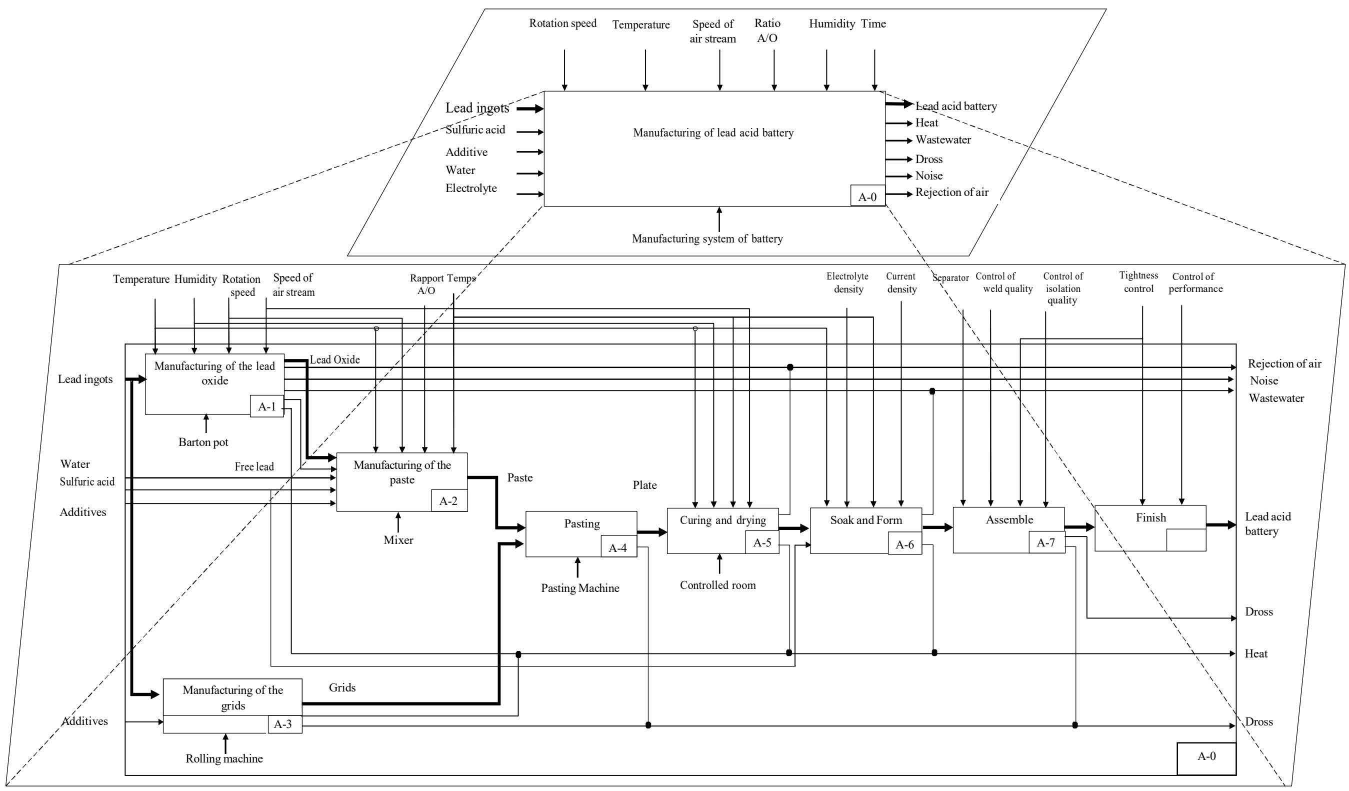

Fig. 2. Diagram of lead acid battery manufacturing.

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III. FMECA ANALYSIS OF LEAD ACID BATTERY DEGRADATION DURING THE MANUFACTURING PROCESS

The analysis of the lead acid battery degradation is based on the FMECA in order to classify the causes and determine the critical causes by calculating of the risk priority number (RPN). The criticality index RPN is calculated for each failure, from the multiplication of the three criteria (severity index S, occurrence index O and detection index: D) [8-10]:

$$RPN= S.O.D \quad (1)$$

The factors of severity, occurrence and detection are evaluated using a numerical index. According to formula 1, severity index refers to the immensity of the failure impact on the use and the rest of the process (Table.1).

Occurrence index refers to the probability of a failure to occur, which is described in a qualitative way (Table.2). A grate with a subjective reading is given because of the absence of an experience feedback on a similar process. Detection index refers to the probability of detecting a failure before it can occur (Table.3). In this context, two gates are proposed: a first according to the efficiency of detecting the fault in the manufacturing process, a secondary based on the type of implementation detection approach (unit operator control, automatic control 100%, measurement control, etc.) and their probability of detection.

TABLE I
SEVERITY RATING SCALE

Scale S	**Description**	**Criteria**
1	Safely	Minimal effects don't cause any influence on the following steps of the manufacturing process and no disturbance during the operation
4	Average	Minor effect causing only a slight disturbance on the following steps of the manufacturing process and a minor disturbance during the operation
7	Significant	Significant effect causing a disturbance on the following steps of the manufacturing process and degradation of battery performance
10	Catastrophic	Failure causing serious problems in the manufacturing process and a bad function of the battery

TABLE II
OCCURRENCE RATING SCALE

Scale O	**Description**	**Criteria**
1	Practically insignificant	Occurrence probability of failure modes is practically insignificant
4	Rarely	Defects rarely occurred in the manufacturing process of the battery which is associated with the misuse of manufacturing means
7	Occasional	Defects occasionally occurred in the manufacturing process of the battery which is associated with a decreasing of the severity of the verification procedure or a wrong dosage of the products and additives
10	Frequent	Defects frequently occurred in the manufacturing process of the battery which is associated with a bad composition of the paste (the structure of the non tetrabasic paste "4BS")

TABLE III
DETECTION RATING SCALE

Scale D	**Description**	**Criteria**
1	Almost certain	Efficient Detection. Very low probability of not detecting before the end of the operation (100% automatically controlled)
2	High	There is a risk that the detection is not effective. Low probability of not detecting the failure before the end of the operation (unitary control by operator)
3	Low	Detection is not easy. High probability of not detecting the failure before the end of the operation (random audits or control by sampling not suitable)
4	Very low	The detection means is not reliable. Very high probability of not detecting the failure before the end of the operation (no control, no visible defects)

The possibility of the failures occurring (O) and their severity (S) were also rated on a scale of 1, 4, 7 and 10. The highest ranking indicates the greatest probability of failures and very severe effect of the failure on battery. Each failure mode was identified whether or not the failure is likely to detect on a scale of 1, 2,3 and 4, where 4 indicates the least likely chance of detecting the failure prior to occurring. From these tables, a high value of criticality index represents a low score while a low value represents a better score. In this study, RPN value can vary between 1 and 400 and failures mode will prioritize according to their numbers.

The FMECA groups the various phenomena that create the degradation of the lead acid battery during the manufacture process and their criticality in Table 4.

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TABLE III
FMECA FOR THE MANUFACTURE PROCESS OF LEAD ACID BATTERY

Function	**Failure modes**	**Effects**	**S**	**Causes**	**O**	**D**	**RPN**	**Recommended action**
Manufacture of lead oxide	Low quality of lead oxide	Quantity of free lead outside the range 18-28wt%, Quantity of β-PbO outside the range 55-30wt%, Median pore diameter of particles beyond the range 1.50-2.64µm, Total pore volume of particles beyond the range 0.20-0.298cm3g-1, Specific surface area of particles outside the range 0.55-0.84m2 g-1	4	Bad adjustment of Hammer mill	4	2	32	Overhaul Preventive maintenance
				Bad function of classifier	4	2	32	Preventive maintenance
				Bad function of reactor	4	2	32	Overhaul Preventive maintenance
Paste mixing	Low quality of paste	Crystal size above 2µm, Surface area of the crystal beyond the range 1.26 ± 0.06m2g-1, Total volume pore of the crystal above 0.148cm3g-1 , Moisture content of the paste outside the range of 11-12%, Density of the positive paste outside the range of 3.90-4.40 gcm-3, Density of the negative paste outside the range of 4.10-4.50 gcm-3, Amount of 1BS above 10wt%	7	Low quality of lead oxide	10	3	210	Increase the sampling frequency
				Ratio A/O beyond the limits	7	1	49	Overhaul
				Bad function of the mixer	4	2	56	Overhaul Preventive maintenance
				Wrong dosage of additives	7	1	49	Overhaul
Manufacture of grid	Low quality of grid	Very thick Very fine grid	7	Wrong composition of the alloy	7	1	49	Overhaul
				Low geometry	4	4	112	Detect and identify the problem
				Bad function of the mould	4	2	56	Preventive maintenance
				Long cooling	4	1	28	Overhaul
Pasting	Low quality of pasting	Low adhesion of the paste on the grid	10	Low quality of paste	10	3	300	Increase the sampling frequency Adding additives
				Low quality of grid	7	3	210	Increase the sampling frequency Adding additives
				Bad function of pasting machines	4	2	80	Preventive maintenance
Curing and drying of plate	Low quality of curing and drying	Low adhesion of the active material, Specific surface area beyond the range 0.8- 1m2g-1, Size crystals above 10µm, amount of free lead into the positive plates below 1%, Amount of free lead	10	Low recrystallization and interconnection of paste particles	10	3	300	Increase the sampling frequency Controlling the climatic conditions
				Low grid oxidation and low formation of corrosion layer	7	3	210	Increase the sampling frequency Controlling the climatic conditions

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		in the negative plates below 5%, Moisture content of the plate below 0.2%, Low cohesion, Presence of cracks		Fault quality of drying	7	3	210	Increase the sampling frequency Controlling the climatic conditions

Function	Failure modes	Effects	S	Causes	O	D	RPN	Recommended action
Soaking and formation of plate	Low quality soaking and formation	Surface specific of the positive plate beyond the range 2-7 m2g-1, Surface specific of the negative plate beyond the range 0.6-1 m2g-1, Size of crystals outside the range 15-20 nm, Content of lead dioxide PbO2 in PAM outside the range 88-92% , Content of spongy lead Pb in NAM outside the range 92-94%	10	Bad conversion of 3BS in the negative plate	10	3	300	Increase the sampling frequency Controlling the climatic conditions
				Bad conversion of 4BS in the positive plate	10	3	300	Increase the sampling frequency Controlling the climatic conditions
				Low electrical penetration into the pores	7	3	210	Overhaul
				Fault quality of formation	7	3	210	Overhaul

During the manufacturing process, a severity value equal to 10 is related to the bad formation of 4BS particles on the plate and poor adhesion of the plate. In addition, a severity value equal to 7 corresponds to the low quality of the paste and grid. Further, a severity value equal to 4 is associated with a low quality of lead oxide. However, the bad function of the machine usually has a detection value 2. In addition, a detection value equal to 1 is usually associated with a wrong dosage of additives and products. The bad formation of 4BS particles on the plate and the poor adhesion of the plate have a detection value 3.

The failure modes during the manufacture process of the lead acid battery are the low quality of lead oxide, low quality of paste, low quality of grid, fault quality of pasting, fault quality of curing and drying, fault quality of soaking and formation.

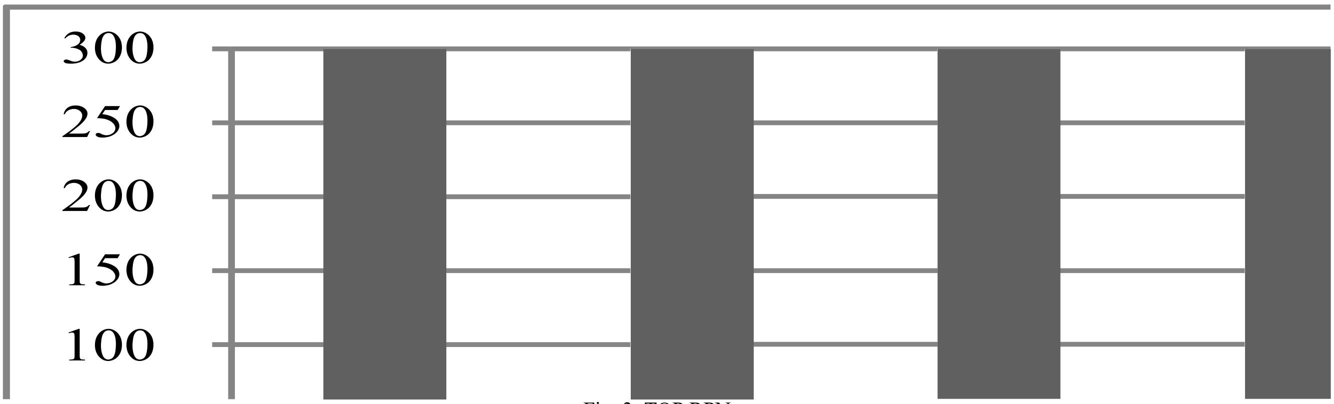

Fig. 3. TOP RPNs

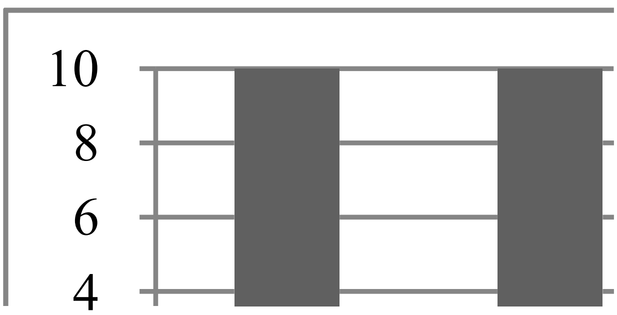

Fig. 4.Top failure modes depending on severity

According to the output of Table.4, the highest priorities of RPNs are concluded in Fig. 3. The critical causes of degradation of lead acid battery depending on the RPN refer to a low quality of paste, a low grid oxidation and low formation of corrosion layer, a bad conversion of 4BS in the positive plate and bad conversion of 3BS in the negative paste. The failure modes depending on severity index are shown in Fig. 4. The first priorities are the low quality of pasting, curing and drying, soaking and formation with highest severity ranking 10. The low qualities of paste and grid have same severity ranking 7.

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A recapitulation of criticality calculation of the failure modes of lead acid batteries during manufacturing processes is shown in Table.5.

TABLE IV
CLASSIFICATION OF FAILURE MODES

Failure modes	Total criticality	Percentage of criticality
Low quality of lead oxide	96	3.16%
Low quality of paste	364	12%
Low quality of grid	245	8.07%
Low quality of pasting	590	19.44%
Low quality of curing and drying	720	23.72%
Low quality of soaking and formation	1020	33.61%
Total	3035	100%

The top failure modes with high criticality refer to low quality of pasting, curing and drying, soaking and formation. Therefore, improving the quality of the lead acid battery during manufacture process requires applying a corrective action that will reduce the occurrence, severity and detection, and that singly or in combination. Reducing the occurrence is to redesign the process for example by replacing manual operations by automated operations, by implementing preventive maintenance, adding additives, by controlling the climatic conditions (controlled temperature, etc ...). In addition, the reduction of severity is to reduce the impact of the failure modes on the lead acid battery quality. In order to reduce the no detection, increase the sampling frequency or change control processes.

IV. Conclusions

The identifying, controlling and decreasing potential failures in the lead acid battery manufacturing are crucial needs. This study proposed a procedure that combined SADT and FMECA analysis to improve the reliability of lead acid battery in the manufacturing process. The SADT used to model the manufacturing process of lead batteries (manufacture of lead oxide, paste mixing and grid, the process of pasting, curing, drying, soaking and formation of the plate, assembly and finishing procedure). Then, the FMECA is used to identify the critical parameters that might affect the reliability of lead acid battery degradation during the manufacturing process. Potential effects of failures are evaluated with their severity value and then the causes and occurrence value are calculated. The Detection value was assigned to the failure mode, and finally the R.P.N value is calculated. Then, the critical causes that might affect the reliability of lead acid battery are identified. Finally, this study allows adducing an improvement in the manufacturing process in order to increase the lifetime of battery during operation process.

This study allows demonstrate that the low quality of soaking and formation process causes the lead acid battery degradation in the order of 33.61%. In this context, the authors propose as a perspective of this paper to provide an improvement in the soaking and formation process through the development of suitable algorithm of formation current to avoid the battery degradation.

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