

Seal strength improvement of valve-regulated lead-acid (VRLA) battery

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Abstract: This research has two objectives. The first objective is to study the effect of assembly process factors on the seal strength of the VRLA battery. The second objective is to find the optimal setting of significant parameters to maximize the seal strength to reduce the defective rate from air leakage defect. This research applied the design of experiment (DOE) technique using the two-level full factorial design to screen out the factors and then used the face-centered central composite design to help find the relationship between the seal strength and the significant factors. It was found that the factors which significantly affect the seal strength were the stopper distance of the case, the stopper distance of the lid, and the melting time. The optimization technique helped determine that the machine setting should be at the stopper distance of the case at 34.97 mm., the stopper distance of the lid at 77.95 mm., and the melting time at 3.1 second to maximize the heat seal strength. After improvement, the defective rate from air leakage defect significantly decreased from 0.12% to 0.01%.

Keywords: *VRLA Battery, Design of experiment (DOE), Defective reduction, Seal strength*

I. INTRODUCTION

A valve-regulated acid-lead (VRLA) battery is commonly used in automatic motorcycles. A major defect found in the assembly process of the VRLA battery was air leakage. The air leakage problem occurs when the seal strength between the battery case and the lid is too low. Thus, there is a need to understand the relationship between the assembly process factors and the seal strength. Then, the optimal levels of those factors should be found to help increase the seal strength and reduce the defectives from the air leakage problem. To determine this relationship, the experiments have to be performed efficiently. The design of experiment (DOE) technique is an appropriate tool for this purpose. After obtaining the experimental results, a statistical analysis and optimization technique are the main tools for testing the significance of factors and finding the optimal levels of those process factors.

II. LITERATURE REVIEW

Since the discovery of the lead-acid battery by Plante in 1859, there has been a continuous evolution of the battery including the valve-regulated lead-acid (VRLA) battery [1]. There were a replacement of early glass container or case by hard rubber and later by high impact Polypropylene (PP) [2]. The first commercial units were devised by Sonnenschein GmbH in the 1960s [3].

Polypropylene (PP) is one of the most common plastic used in the manufacturing of lead-acid battery cases and lids [4]. It has many desirable properties when compared to other thermoplastics. These properties are high melting point, low density, high tensile modulus, and low cost. However, PP has relatively low melt strength and exhibits no strain hardening behavior in the melt state due to its linear molecular structure [5]. A critical process during the manufacture of the battery is the heat sealing process, which helps the formation of a good bond between the PP plastic lid and case. The strength of the bond is determined by the tensile testing. A number of factors contribute to the strength of the seal. These factors include the extent of the stopper distance, the holding time against the heating plates and its temperature [6], [7]. There were some researches, which studied the effect of a degradation of virgin and recycled polypropylene on the seal strength of the lead acid battery cases. Moreover, there were many researches that improve the performance of the VRLA battery concerning with chemical and electrical properties such as the chemical composition of lead alloy, and the discharge capacity. However, there were a few researches that study the performance of the VRLA battery resulting from the factors in real production processes such as the assembly process. The machine setting during the assembly process has significant effect to VRLA battery defectives. The objective of this paper is to find out the significant assembly process factors and the best setting of those factors to increase the seal strength and then mitigate the problem of air leakage of the VRLA battery.

III. PROBLEM DESCRIPTION

In the case study factory, the major defect found in the assembly process was the air leakage. It was found that the proportion of defectives from air leakage is 0.12%. The Pareto chart shown in Fig.1 showed that

the air leakage defect caused 71.9% of total defectives. The air leakage occurred in the heat sealing process, which connected the case to the lid. The air leakage was tested using the leak tester. The air leakage problem was related to the seal strength of the bond between the plastic case and the lid. The dot plot shown in Fig. 2 and the statistical t-test showed that the batteries that had air leakage defects had the lower seal strength than the normal batteries at the significance level of 0.05. The means of the seal strength of normal batteries and batteries with air leakage were 2.85 kg./mm. and 0.95 kg./mm. respectively.

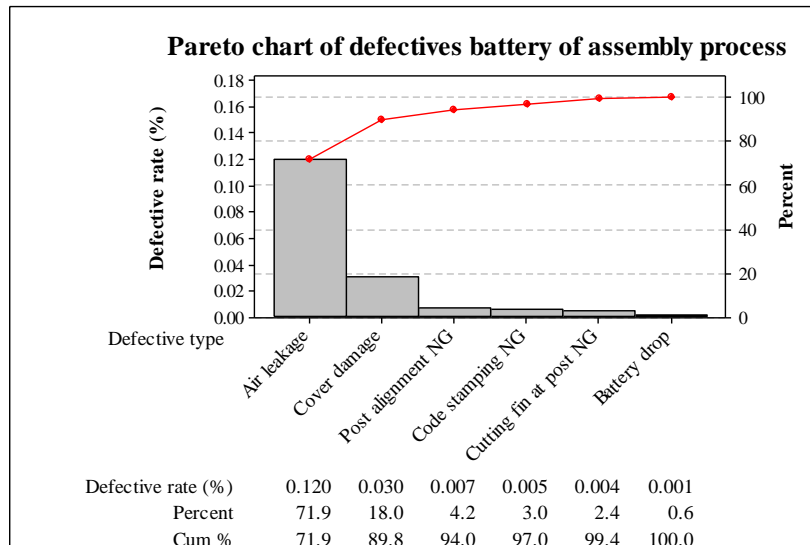


Fig.1 Pareto chart of defective batteries from the assembly process

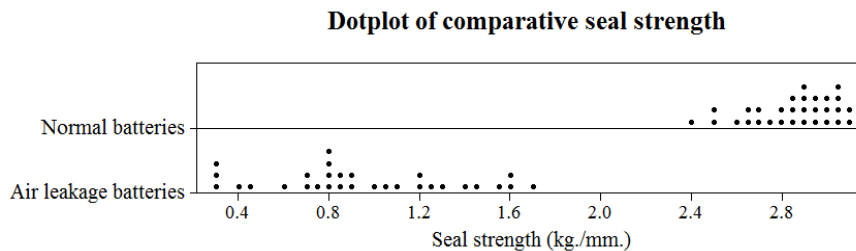


Fig.2 Comparative dot plots of seal strength between normal and air leakage batteries

IV. METHOD

4.1 Experimental designs

4.1.1 Screening experiment with two-level full factorial experimental design

This research studied the effect of five factors on the seal strength. These factors were main factors related in the heat sealing process. These factors were the stopper distance of the case, the stopper distance of the lid, the heating plate temperature, the holding time while sealing the case and the lid, and the melting time. First, the experiments using the two-level full factorial design (2^5) with a single replicate and three center points were performed to screen out the insignificant factors. The two-level factorial design provided a fewer number of runs for the screening purpose. The center points were added to check whether the curvature effect was presented. The two levels which were tested for each factor were determined from the bound of possible factor setting and from the literature review. The levels are shown in Table 1.

Table1 Factors and factor levels of the heat sealing process

Symbol	Factors	Unit	Levels of Factors		
			Low	Center	High
A	Stopper distance of case	mm.	34.1	35.1	36.1
B	Stopper distance of lid	mm.	77.0	78.0	79.0
C	Heating plate temperature	degree Celsius	325	330	335
D	Holding time	second	4.5	5.0	5.5
E	Melting time	second	2.5	3.0	3.5

4.1.2 Response surface methodology with the face-centered central composite design

After obtaining the significant factors from the screening experiment above, the Response Surface Methodology (RSM) was then used to find the equation of non-linear relationship between the response and the factors. Next, the optimal level of the significant factors was determined from the equation to maximize the seal strength of the VRLA battery. The face-centered central composite design was used instead of the spherical central composite design to avoid the experimental runs at the extreme settings. In addition, the face-centered CCD does not require as many center points as the spherical CCD [8].

V. ANALYSIS OF RESULTS AND DISCUSSION

5.1 Analysis of results of the screening experiment

The experimental data were analyzed using the Analysis of Variance (ANOVA) method. The significance level (p-value) of each main effect and interaction effect was shown in Table 2. It can be seen that the effects that were statistically significant at the significance level of 0.05 were the main effects of the stopper distance of the case (A), the stopper distance of the lid (B), and the melting time (E). The two-way interaction effect between the stopper distance of the case and the stopper distance of the lid (A*B) and also the curvature effect were found to be significant at the significance level of 0.05. Factors C and D, which were the heating plate temperature and the holding time were screened out. The remaining three significant factors were then further analyzed using the face-centered central composite design.

Table 2 ANOVA results of the two-level full factorial experimental design.

Source	DF	Sum of Square	Mean Square	F	P - Value
Main Effects	5	11.7012	2.3402	19.47	0.000
Stopper distance of case (A)	1	9.3420	9.3420	77.74	0.000
Stopper distance of lid (B)	1	1.3686	1.3986	11.64	0.003
Heating plate temperature (C)	1	0.0116	0.0116	0.10	0.759
Holding time (D)	1	0.3301	0.3301	2.75	0.115
Melting time (E)	1	0.6188	0.6188	5.15	0.036
2-Way Interactions	10	2.1009	0.2101	1.75	0.145
Stopper distance of case*Stopper distance of lid (A*B)	1	0.9079	0.9079	7.55	0.013
Stopper distance of case*Heating plate temperature (A*C)	1	0.4209	0.4209	3.50	0.078
Stopper distance of case*Holding time (A*D)	1	0.0893	0.0893	0.74	0.400
Stopper distance of case*Melting time (A*E)	1	0.2363	0.2363	1.97	0.178
Stopper distance of lid*Heating plate temperature (B*C)	1	0.0751	0.0751	0.62	0.440
Stopper distance of lid*Holding time (B*D)	1	0.0011	0.0011	0.01	0.924
Stopper distance of lid*Melting time (B*E)	1	0.1188	0.1188	0.99	0.333
Heating plate temperature *Holding time (C*D)	1	0.0639	0.0639	0.53	0.475
Heating plate temperature *Melting time (C*E)	1	0.0000	0.0000	0.00	0.988
Holding time*Melting time (D*E)	1	0.1876	0.1876	1.56	0.228
Curvature	1	3.6676	3.6676	30.52	0.000
Residual Error	18	2.1631	0.1202		
Lack of Fit	16	2.1598	0.1350	82.65	0.012
Pure Error	2	0.0033	0.0016		
Total	34	19.6328			

5.2 Analysis of results of the RSM experiment

The Analysis of Variance (ANOVA) was performed to the results obtained from the face-centered central composite design experiment. It was found that the all linear terms, all square terms, and all interaction terms of the three factors excluding BE interaction were significant at the significance level of 0.05.

Table 3 ANOVA results of RSM and face-centered central composite design

Source	D F	Sum of Square	Mean Square	F	P - Value
Regression	9	9.48190	1.05354	124.13	<0.0005
Linear	3	0.52814	0.17605	20.74	<0.0005
Stopper distance of case (A)	1	0.42849	0.42849	50.59	<0.0005
Stopper distance of lid (B)	1	0.05476	0.05476	6.45	0.0290
Melting time (E)	1	0.04489	0.04489	5.29	0.0440

Square	3	8.75233	2.91744	343.74	<0.0005
Stopper distance of case*Stopper distance of case (AA)	1	7.09241	1.30928	154.26	<0.0005
Stopper distance of lid*Stopper distance of lid (BB)	1	1.50152	0.97357	114.71	<0.0005
Melting time*Melting time (EE)	1	0.15840	0.15840	18.66	0.0020
Interaction	3	0.20144	0.06715	7.91	0.0050
Stopper distance of case*Stopper distance of lid (AB)	1	0.14311	0.14311	16.86	0.0020
Stopper distance of case*Melting time (AE)	1	0.05281	0.05281	6.22	0.0320
Stopper distance of lid*Melting time (BE)	1	0.00551	0.00551	0.65	0.4390
Residual Error	10	0.08487	0.00849		
Lack-of-Fit	5	0.08432	0.01686	153.31	<0.0005
Total	19	9.56678			

The backward regression analysis was performed in order to find the equation of the relationship between the response and the significant experimental factors. The response surface model was shown in equation (1).

$$Y = 3.105 - 0.207X_A - 0.074X_B + 0.067X_E - 0.690X_A^2 - 0.595X_B^2 - 0.240X_E^2 - 0.134X_A X_B + 0.081X_A X_E \quad (1)$$

where:

Y = Seal strength (kg./mm.)

X_A = Stopper distance of the case (mm.)

X_B = Stopper distance of the lid (mm.)

X_E = Melting time (second)

The model shown in equation (1) had the R² of 99.11%. This high value of R² showed that this model can explain 99.11% of the variability in the data. Thus, this model was good enough to predict the relationship between the heat seal strength and the three factors.

5.3 Optimization of factor levels

The response surface model was solved to obtain the optimal levels of factors. The optimization result in Table. 4 and Fig. 3 showed that it was predicted that the maximum heat seal strength of 3.125 kg./mm. could be obtained by setting the stopper distance of the case at 34.97 mm., the stopper distance of the lid at 77.95 mm., and the melting time at 3.1 seconds.

Table 4 Optimum factor levels and heat seal strength response

Factors and Response	Symbol	Values	Unit
Stopper distance of case	A	34.97	mm.
Stopper distance of lid	B	77.95	mm.
Melting time	E	3.1	second
Heat seal strength	Y	3.125	kg./mm.

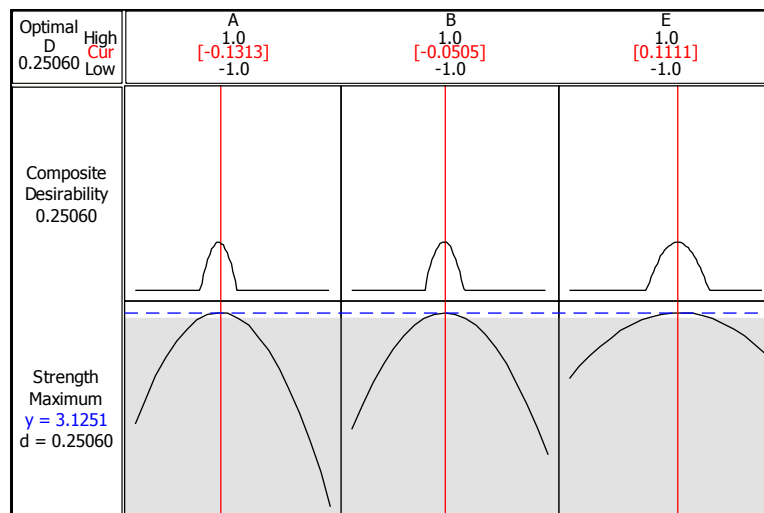


Fig.3 The optimization result of heat seal strength

The results can be discussed as follows. The highest seal strength was obtained when the stopper distance of the case, the stopper distance of the lid, and the melting time were set around the middle values. In general, the seal strength was decreased as the stopper distance of the case and the lid were increased, and the melting time was decreased. The reason was that when the stopper distance was increased and the melting time was decreased, the polypropylene plastic was not melted enough to form a good bond between the plastic case and the lid. On the other hand when the stopper distance of the case and the lid were decreased, and the melting time was increased, the polypropylene plastic was over melted and then stick on the heating plate of the machine instead of sticking on the right position between the case and the lid. Thus, the good bond between the case and the lid was not obtained. Thus, the middle levels of these factors as shown in Table 4 were the optimal setting.

5.4 Confirmatory results

After implementing the new factor level setting at the heat sealing machine for three months, the average defective rate (%) of air leakage batteries was decreased from 0.12% to 0.01% as shown in Fig. 4.

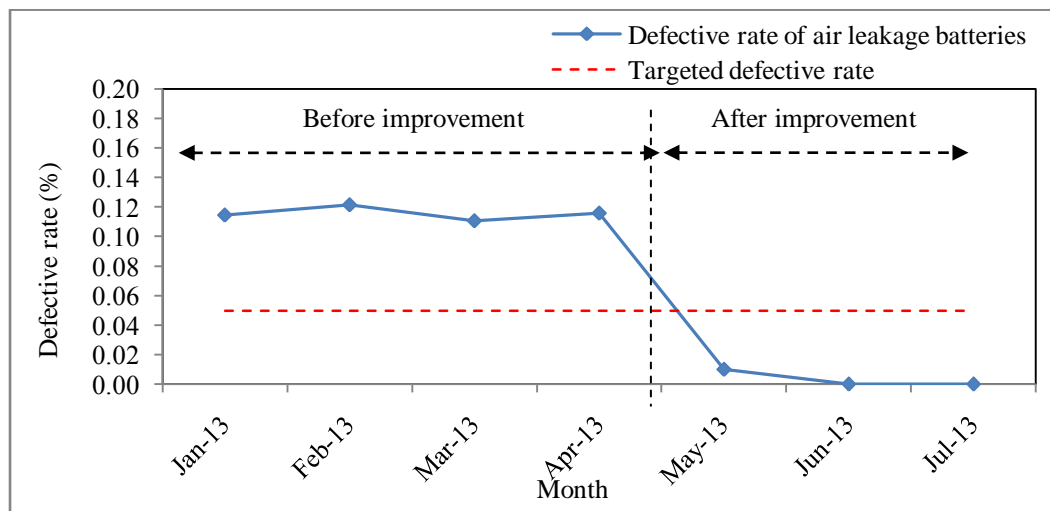


Fig.4 Comparative defective rates of air leakage batteries before and after improvement

VI. CONCLUSION

This paper presented the statistical experiment design methodology to decrease the defective rate from air leakage of the VRLA battery. The screening experiment and the response surface methodology were applied to help identify the significant factors in the heat sealing process and indicate the optimal levels of those factors. It was found that the stopper distance of the case, the stopper distance of the lid, and the melting time are significant factors that affect the heat seal strength. The optimization technique helped indicate that the machine setting should be at the stopper distance of the case at 34.97 mm., the stopper distance of the lid at 77.95 mm., and the melting time at 3.1 seconds to maximize the heat seal strength.

After improvement, it was found that the defective rate from air leakage defect significantly decreased from 0.12% to 0.01%, which is equal to 92% defective reduction.

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