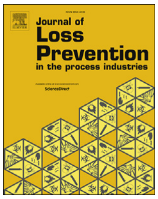
Contents lists available at ScienceDirect

Journal of Loss Prevention in the Process Industries

journal homepage: www.elsevier.com/locate/jlp



Safety analysis of lithium-ion battery by rheology-mutation theory coupling with fault tree method

Chuang Qi [a], Yan-Li Zhu [a, *], Fei Gao [b], Song-Cen Wang [b], Kai Yang [b], Qing-Jie Jiao [a]

[a] *State Key Laboratory of Explosion Science and Technology, Beijing Institute of Technology, Beijing 100081, China*
[b] *Battery Energy Storage Technology Laboratory, China Electric Power Research Institute, Beijing 100192, China*

ARTICLE INFO

Article history:
Received 17 December 2016
Received in revised form
12 May 2017
Accepted 7 June 2017
Available online xxx

Keywords:
Lithium-ion battery
Explosion
Rheology mutation theory
Fault tree method

ABSTRACT

The safety of LIB (lithium-ion battery) was analyzed by the rheology-mutation theory and FTA (fault tree analysis) method. The explosion process of LIB can be viewed as a rheology-mutation process. The process of safety rheology with time can be divided into three stages: decelerated, stable and accelerated growth stage, respectively. The physical model and mathematic model were built to estimate the probability of LIB explosion based on the rheology-mutation theory. The influence of different parameters, like external force, strength coefficient and wear coefficient, on probability of LIB explosion were discussed. The results showed that the external force is the most important parameter which controls the overall growth trend of the probability of LIB explosion. Strength coefficient determines the resistance of LIB to the external stimulation. Wear coefficient controls the rate of rheology and mutation. The external forces, strength coefficient and wear coefficient were influenced by the factors, which lead to the LIB explosion. In order to analyze these factors, a fault tree of LIB explosion was built. The minimum cut sets and the structure importance degree coefficient of each basic event were calculated through Boolean algebra method. The collision is the most important factor that influences the LIB explosion. The protective measures for the safe use of LIB were proposed.

1. Introduction

LIBs, with long cycle life, high voltage, low self-discharge and high energy density, are widely used in portable equipments, electric vehicles and stationary storage systems. The number of used LIBs is increasing exponentially every year. Due to the high energy density material and flammable electrolyte, LIBs can easily trigger catastrophic events, like Samsung mobile phone explosion and BYD E6 electric-only powered car explosion-occurred in Shenzhen. The users may get injured by the detonation wave and fire of LIB explosion (Wang et al., 2015). The larger scale commercialization of LIB has been hindered because of the safety problem. LIB safety has received much attention.

LIB safety has been researched for more than ten years. The compounds of LIB, electrolyte, cathode and anode, were studied widely and deeply on their thermal stability using many kinds of thermal techniques (Wang et al., 2010), like differential scanning calorimetry (DSC) (Lopez et al., 2015; Maleki et al., 1999; Yun et al., 2016), accelerating rate (ARC) (Richard and Dahn, 1999), thermogravimetric (TG) (Maleki et al., 1999) and C80 calorimetry (Saito et al., 1997). Overcharging test (Yuan et al., 2015), penetration test (Lee et al., 2012) and impact test (Doh et al., 2008) on battery and battery pack were also performed. Furthermore, the state of lithium ion battery safety was studied by many different methods. Hazard levels method (Ashtiani, 2008; Cabrera et al., 2016) originally proposed by European Council for Automotive Research and Development (EUCAR) was used to classify the hazard levels of battery in some standards and documents. Ashtiani (Ashtiani, 2008) introduced a methodology called hazard modes and risk mitigation analysis to quantify the battery hazard levels. These studies were mostly focused on the safety of LIB material, mechanism and hazards of LIB explosion. Reports about the evolvement rule and factors analysis of LIB explosion were few. Therefore, a comprehensive analysis about the LIB explosion is significative and necessary.

Rheology-mutation theory is proposed to analyze an accident. Every accident has two characteristics which are rheological and mutational (Zhou and Liu, 2009). The process of LIB explosion also has these two characteristics. Therefore, the rheology mutation

---

* Corresponding author.
E-mail address: 3120140073@bit.edu.cn (Y.-L. Zhu).

http://dx.doi.org/10.1016/j.jlp.2017.06.006
0950-4230/

theory is suitable for safety analysis of LIB in the life cycle. Fault tree method (FTA) is used to analyze the factors which lead to LIB explosion. Compared to other methods, FTA is structured in graphical representation and easy for readers to comprehend.

The probability of LIB explosion increases with time. With the users' security awareness of LIB usage declining and LIB degradation, the probability increases continually but with a varying rate. The growth rate decreases firstly, keeps stable and finally increases quickly. According to the growth rate of probability, the evolution of LIB safety in the life cycle can be divided into three stages: decelerated, stable and accelerated stage, respectively. The process of LIB explosion can be considered as a rheology and mutation process. Therefore, rheology-mutation theory was employed to analyze the LIB explosion. Physical model and mathematic model were built to analyze the probability of LIB explosion quantitatively. Since the parameters of rheology and mutation theory are influenced by many factors, like high temperature, soaking and overcharge, the probability of LIB explosion is affected by these parameters indirectly. Hence, FTA method was used to analyze the factors and a fault tree of LIB explosion was built. The structure importance degree coefficient of each basic event was calculated. Some protective measures were put forward on the basis of the above analysis.

2. Safety evolution of LIB based on rheology-mutation theory

2.1. Rheology-mutation theory

A process of safety evolution follows the safety rheology and mutation law (Xue, 2005). According to the rheology-mutation theory, safety is viewed as a mass body and safety damage represents quality loss of the body. In other words, the safety damage represents the degree of danger. It determines the security status and is proportional to the probability of accident. As shown in Fig. 1, the process of safety rheology and mutation can be expressed as four stages: gestation, stabilization, growth and mutation stage. Gestation stage (O'A) is the initial stage of one thing. O′ is the point of initial safety damage. The safety damage increases slowly during the running-in period. After this period, the safety damage keeps constant in AB stage. With aging of the thing, the safety damage begins to accelerate in growth stage (BC). If the damage exceeds the limit of maximum inherent safety damage capacity, the thing will mutate, shown as the CD stage in Fig. 1. C is called the point of critical damage (Cao and Dong, 2003). The safety damage velocity is shown as the dotted line in Fig. 1. The velocity decreases to almost zero, remains for a while, and then increases at a high rate until out-of-control.

According to the results of some researches (Chen et al., 2006; Balakrishnan et al., 2006; Vetter et al., 2005), it was found that the safety evolution of LIB was in accordance with rheology and mutation law. Therefore, the process of the safety evolution of LIB can also be divided into the four parts. Since the growth stage of LIB safety evolution is very short and difficult to distinguish it from the later stage, this stage can be combined with the latter, mutation stage, as shown in Fig. 2. According to the safety damage velocity and acceleration, the three stages were redefined: decelerated, stable and accelerated stage, respectively. Point O′, which is shown in Fig. 2, represents the initial safety damage of LIB safety damage. The initial safety damage is inversely proportional to the LIB production quality, which is closely associated with the manufacturing process. The manufacturing process mainly consists of sealing subassembly, winding, assembly and liquid injection process. The defects of process will cause safety damage. For instance, insufficient riveting strength of LIB shell will cause the battery internal resistance increasing. Conversely, excessive riveting strength will result in the loss of insulation and tightness (Xue, 2008). At the first stage, the safety damage (represented by the safety rheology and mutation curve) increases slowly and the slope is less than zero. In the early life cycle of LIB, the safety damage of LIB is mainly caused by the running-in of various battery parts, partial internal short circuit with burrs (Lopez et al., 2015) and users' unskilled operation. All these factors may create minor damage to LIB. With prolonged time of LIB use, the safety damage approaches to a constant value since the LIB operating properly and being used proficiently. The second stage is called stable stage. The safety damage velocity and acceleration trend to zero. At the third stage, the safety damage velocity and acceleration increase quickly. After LIBs is used for a long time, the behavior of unreasonable LIB use may occur since the users' security awareness may be reduced by complacency (Hung, 2016). In addition, the LIB system aging leads to lithium-ion deposition, battery management system failure and connection pieces loosening. These factors probably raise some unexpected events, like overcharge, over discharge, short circuit et al., which leads to the essential damage of LIB. If the safety damage exceeds the limit, LIB will explode.

2.2. Rheology-mutation physical model

The physical model is built based on the rheology mutation theory. As shown in Fig. 3, there are four primary functional elements in the model. They are safety quality body, safety friction element, safety damper element and safety reversible element, respectively. The model consists of 5 regions: generalized force (I), immediate recovery (II), slow recovery (III), essential damage (IV)

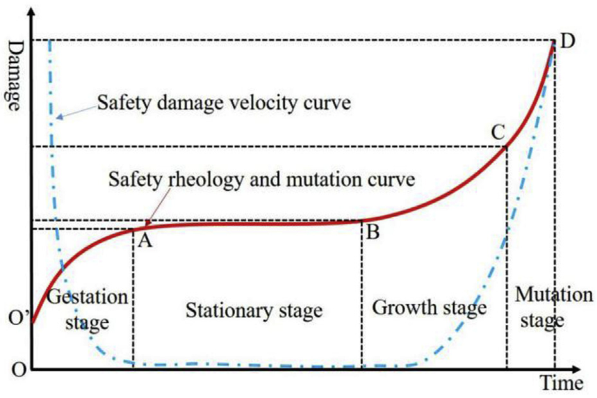


Fig. 1. Process of safety rheology and mutation (Cao and Dong, 2003).

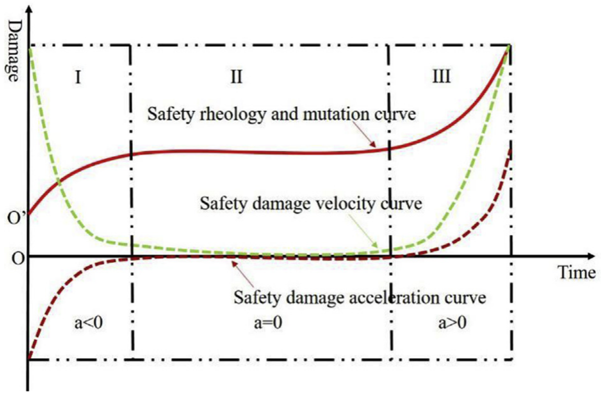


Fig. 2. Safety rheology and mutation of LIB (a): acceleration stage, (I): decelerated stage, (II): stable stage, (III): accelerated stage.

Please cite this article in press as: Qi, C., et al., Safety analysis of lithium-ion battery by rheology-mutation theory coupling with fault tree method, Journal of Loss Prevention in the Process Industries (2017), http://dx.doi.org/10.1016/j.jlp.2017.06.006