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Metallurgical and mechanical methods for recycling of lithium-ion battery pack for electric vehicles

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ABSTRACT

Due to enormous growth of production of electric vehicles, it is estimated by the year 2020 about 250,000 tons of battery must be disposed or recycled. The technology to recycle this much amount of batteries in a single year does not exist., neither does the methods for recycling are standardized because of different configurations of battery packs. A challenge strictly poses on how to deal with lithium ion batteries, which are embedded in hundreds or more in a battery pack. Furthermore, the recovery of materials from the battery in the pack is essential to ensure the growth and sustainability of the electric vehicle market. It is desirable to establish a framework that is semi-automated/automated for ensuring faster disassembly of battery pack, identification and detection of residual energy of batteries in packs and recovery of materials from batteries. This review paper summarizes the two main basic aspects of recycling battery packs: mechanical procedure and chemical recycling (metallurgical). The work summarizes the existing recycling technology in these two aspects and identifies important research problems in the process of recycling of pack such as (i) automatic and intelligent recovery system, (ii) efficiency and safety disassemble of battery pack (iii) Adjustment of Chaos in recycling market (iv) Recovery processes for slag, electrolyte and anode, (v) Application in industrial scale, and (vi) development of recycling methods for new batteries having components with different properties. This paper also proposes a framework to push the recycling process from conception to practicality, both on government incentive polices and effective recycling technology.

1. Introduction

Within the last two decades, lithium-ion batteries (LIBs) technology has been extensively applied in wide-scale electric storage instruments, such as portable electronics, renewable power systems, and electric vehicles (EVs) because of their outstanding characteristics of small size, high voltage and energy density, long cycle life, and low self-discharge (Nitta et al., 2015). For instance, the global consumption of LIBs in 2000 rose to 500 million Li-ion cells, with the growth and expansion of 800% over course of 10 years starting from 2000. Furthermore, the increase of the EVs industry has been undergone a great change in the usage of LIBs. It is predicted that the large amount of spent LIBs in 2020 will surpass 500 thousand tons and 25 billion units (Zeng et al., 2014). With increasing concerns regarding environmental issues (Gaines, 2012) and the limited availability of lithium and cobalt, there have been stringent laws put in place world-wide in order to treat spent LIBs to properly recycle valuable metals as well as toxic chemicals (Meng et al., 2017). Therefore, the development of efficient recycling technologies for spent LIBs has become much attracted in the present time and future.

In recent years, many studies have focused on single recycling methods based on mechanical and metallurgy processes (Meng et al., 2017; Golmohammadzadeh et al., 2017). Mechanical processes comprise of disassemble of battery pack to modules, module to cells as well as the process of crushing single lithium-ion battery and sorting of materials. Metallurgical processes include pyro-, hydro-, bio-metallurgy and hybrid methods.

However, there has been a limited literature that combines both of them. Most of the literature review has been on materials recovery, life cycle assessment,policy development and cost-environmental benefit analysis of recycling of batteries (Wang and Wu, 2017; Awasthi and Li, 2017; Kumar et al., 2017; Liang et al., 2017). Thus, a systematic review

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summarizing the combination of recycling processes (mechanical and metallurgical processes) could pave the way for proposition of framework for efficient and effective recycling of battery pack. In this review paper, we combine the Metallurgical and Mechanical methods used in recycling of battery pack for electric vehicles (EVs). Fundamental recycling of spent Lithium-ion batteries was also summarized in context of metallurgical processes.

The remaining structure of the paper is as follows. Section 2 illustrates the components of lithium-ion batteries for EVs. Details in the recycling processes includes mechanical and metallurgical methods are introduced in Section 3. The critical gaps with new directions of research in the recycling process are discussed in Section 4. Based on research gaps, a framework for recycling of battery module is illustrated in Section 5. Finally, conclusions of the study are discussed in Section 6.

2. Components of lithium batteries for EVs

Electric vehicle (EV) packs typically comprises of battery modules and the battery management system. Battery modules comprises of batteries connected in series and parallel.

The LIB cell is comprised of four fundamental components: anode, cathode, electrolyte separate and shell casing (Xiao et al., 2017). The chemical compositions slightly vary as per manufacturers. The cathode materials in commercial LIBs are usually either lithiated metal oxide or lithiated metal phosphate such as: $LiCoO_2$ (LCO), $LiMn_2O_4$ (LMO), $LiNi_{0.33}Mn_{0.33}Co_{0.33}O_2$ (NMC), and $LiFePO_4$ (LFP). Table 1 shows the summary of upsides and downsides of the electrode materials used in commercial LIBs (Kushnir, 2015; Ordoñez et al., 2016). Carbon materials are used for anode component such as graphite and hard-carbons. These are usually the top choice used in current industrial manufacturers because these involves the combination of low cost, abundant availability, and cycle life. The anode and cathode material are linked with current collector sheets (Cu, Al) through adhesive agent like polyvinylidene fluoride (PVdF) binder. There are various electrolytes for LIBs including liquid electrolytes, polymer electrolytes. Liquid electrolytes are effectively utilized for a variety of battery applications. These consist of lithium salts ($LiPF_6$, $LiBF_4$, $LiClO_4$) dissolved in a single or combination of several organic solvents, e.g. ethylene carbonate (EC), propylene carbonate (PC), and dimethyl sulfoxide (DMSO). Polymer electrolytes have also been widely applied in portable electronics (laptops, smart phones, and tablets…) owing to their lightweight and shape flexibility of battery in any desirable configurations. Common polymer hosts used in LIBs comprise poly(acrylonitrile) (PAN), polyethylene oxide (PEO), polymethylmethacrylate (PMMA), polypropylene oxide (PPO), and many other (Zeng et al., 2014).

A typical LIB contains about 25–30% cathode, 15–30% anode (including current collector sheets), 10–15% electrolyte, 18% cell can, 3–4% separate and 10% other components (Nayaka et al., 2015; Winslow et al., 2017). The chemical composition of some typical LIBs are shown in Table 2 (Winslow et al., 2017). Fig. 1 shows material composition of a $LiNi_{0.33}Mn_{0.33}Co_{0.33}O_2$ battery.

3. Recycling processes

With the rapid development of lithium ion battery and electric vehicles in recent years, the recovery of lithium battery has also become a hot area of research (Liao et al., 2017). From 2008 to 2018, more than 3000 research papers are associated with this topic. In summary, the process of recycling combines two stages (see Fig. 2). At the first stage, mechanical recycle process (also known as physical process), includes disassemble, crushing, screening and separation. The purpose of this process is returning of lithium-ion batteries out of electric vehicles and separation of the cell into particles that can be directly reclaimed by chemical recovery. The main challenges in the physical process are as follows: a) Different design and connection of battery pack enclosure in EVs. b) The un-uniformity of size and shape of battery module and

Table 1
Upsides and downsides of the electrode materials (Kushnir, 2015; Ordoñez et al., 2016).

Material	Voltage vs Li/ Li^+	Specific capacity ($mAh.g^{-1}$)	Volumetric capacity ($mAh.cm^{-3}$)	Advantages	Disadvantages
$LiCoO_2$	3.8	145	550	High Li^+ ion and electronic conductivity, performance	High-priced and harmful Co, low capacity.
$LiFePO_4$	3.4	170	589	Low-priced, environmentally friendly, cycle life, rate capability	Low voltage and energy density, low Li^+ ion and electronic conductivity, high processing-cost,
$LiMn_2O_4$	4.1	120	596	Low-priced and environmentally friendly, rate capability, high Li^+ ion and electronic conductivity	Cycle life, low capacity, severe capacity fade at temperature (55 °C)
$LiNi_{0.33}Mn_{0.33}Co_{0.33}O_2$	3.7	170	600	Better safety and performance than LCO, high voltage	High-priced, harmful Co, Ni, Needs cell balancing and voltage protection
Graphite	0.1	370	–	Low-priced and environmentally friendly, cell voltage	High processing-cost, formation of solid electrolyte interfacial (SEI) layer, low energy density