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A REVIEW ARTICLE ABOUT THE THERMAL RUNAWAY MECHANISM OF LITHIUM BASED BATTERIES

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ABSTRACT

The aim of this paper is fulfilling a review about a safety aspect of lithium-ion and lithium-polymer batteries. These devices are nowadays widely used in entertainment electronics, (for smartphones or laptops), in transportation for electric vehicles. The thermal runaway effect is a known safety concern in lithium-based cells. However, this effect is due to improper production and use, the research of the behaviour of these batteries is getting important, because of the high amount of Li usage requires the development of its recycling. During the recycling process for example during the grinding process the impact can causes such effects like runaway, but even explosion.

1. INTRODUCTION

The principle of the operation is the same for any type of battery; they provide electrical energy through an electrochemical reaction between a positively charged anode and a negatively charged cathode. The performance of the battery and the battery itself can be recharged depending on the battery design and the used materials.

These batteries are made up of cells, and these cells describe the units which made up an anode and a cathode, these can storage energy and can deliver power. A battery can be a single cell (different types of batteries, AA or AAA batteries), or these cells can be combined for a more powerful battery, for example batteries for laptops or even electric vehicles (EV).

In case of Li-ion batteries the positive lithium in the anode becomes positive Li+ ion and an electron. In case of power release these lithium-ions flow through the electrolyte to the cathode, while charging the batteries, this process reversed. These electrolytes are capable to conduct electricity. For the Li-ion batteries, basically there are two different electrolyte types: the liquid and solid electrolytes. The liquid electrolytes consist lithium salts, for example $LiBF_4$, $LiPF_6$ or $LiClO_4$ in organic carbonate solvent. The up-to-date batteries use solid state electrolytes, which are typically ceramics. These lithium metal oxides able to transport the lithium ion through the solid state. These electrolytes have no risk of leaks, which is the main problem of the liquid state electrolytes.

2. THERMAL RUNAWAY

In the event of lithium battery damage, physical impact, excessive heat input or short-circuit, it can trigger this thermal flutter, resulting in explosive energy release accompanied by heat and flame, which is called thermal runaway. This damage

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caused by two different methods: mechanical or electrical abuse [1-2]. The general process of the failure is the follows (Figure 1):

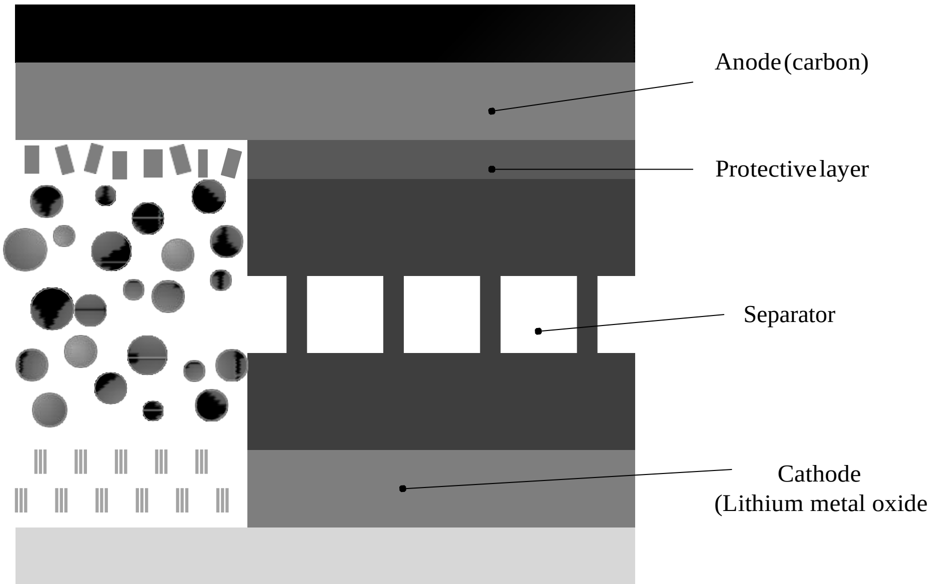

Figure 1.: Thermal runaway in a Li-ion cell

In the first step is the warming up of the cell begins because of impact. Due to the heat, the material of the protective layer decomposes to flammable gases. In the next step the separator will melt, which can even cause short circuit. The final step is the decomposition of the cathode with oxygen gas generation. This oxygen will feed the fire. As a battery for measuring devices, this effect can be a major hazard in an industrial environment [3–6].

In case of thermal runaway, the temperature of the battery heats up instantly from room temperature to about 700 °C. As a result, the electrolyte decomposes on its constituents, which in most cases are methane, ethane, ethylene and other flammable and toxic gases, such as carbon dioxide, carbon monoxide and hydrogen [7]. The cathode also breaks down, which generates oxygen gas. The risk of explosion increases as the pressure builds up in cells. So, this duel hazard listed in the following table:

Table 1: Chemical and electrical hazards

Produced gas	Concentration (%)	Hazard
Methane	5-8	flammable
Ethane	1-3	flammable
Ethylene	3-8	flammable
Propylene	1-3	flammable
carbon-dioxide	~30	asphyxy
carbon-monoxide	~20-25	flammable, toxic
hydrogen	~30	flammable
hydrogen fluoride	0,3	corrosive, toxic
C4+	<1	flammable

This fire chain reaction is induced by the strong reactivity of the lithium. To freeze this reaction is extremely difficult, especially if the amount of the Li is high (for example in the battery packs of the electrical vehicles).

2.1. MECHANICAL ABUSE

The effect from physical or mechanical influences can damage the battery cells, which may cause even explosion. This type of failure is less hazardous, because it can occur in any battery conditions. That means the magnitude of explosion depends on the condition of the battery level. The main mechanical effect is mainly caused by the accidents of the electrical vehicles. Because of the collision, the battery cells are subjected to a high dynamic force, resulting in damage to the battery. To avoid this, the cells are usually placed in an energy-absorbing housing, usually covered by a bottom armour plate.

2.2. ELECTRICAL ABUSE

There are two major types of electrical failures: the first is the external short circuit, and the other is the overcharging. An electrical short circuit occurs when any positive and negative conductor of the cell contact with each other. Due to this fact electricity flows between the anode and cathode, and the battery life will be decreasing. This lifetime depends on the quasi diameter; a bigger wire will cause a much shorter battery life. This high current and high-power consumption will trigger a chain reaction, which begins to warm up and expand the cell. This will increase the internal resistance of the cells, which occur higher heating, and so on. As a result the affected cells will be exploded, and this explosion will release instantaneously due to fire and heat [8].

Most of the short circuit faults occur immediately after their production. That means the faults are caused from the failure of wiring or the soldering. These kinds of errors can be avoided by first connecting the batteries to the installation location with a fuse. The failure types cannot be separated sharply, because a mechanical impact also can create short circuit effects.

The other electrical failure is the overcharging. This is the most common field failure, usually occurs when the charging current is forced through the cells after it reaches its nominal cut-off voltage. This failure mechanism has been investigated by researchers [9], [10]. In case of overcharging, the temperature of the battery fast rising due to the large amount of heat generation. This heat comes from the joule heat and heat generated by the reaction of the anode and cathode.

3. LITHIUM DENDRITES

A group of researchers were able to produce close-up images of finger-like formations that cause serious problems with the lithium-ion batteries. The formation of these dendrites leads to short-circuit formation, which able to cause the overheating or even the burnout of the battery cells. This phenomenon will cause

the destruction of the batteries of the multimedia devices, and even the risk of burns.
To understand the process, the usage of the most modern tools is indispensable. These lithium dendrites discovered by the collaboration of the Stanford University and the US National Accelerator Laboratory, by using of a new microscope type called cryo-electron microscope. With this up-to-date device the form and the formation of the dendrites can be studied. According to the recordings, the resulting dendrites are hexagonal shaped crystals, and these will cause problems when they break through the separator medium, which are between the different parts of the battery (see Figure 1). When the anode and cathode are damaged and directly contact to each other, short-circuit formed, and this short-circuit will cause temperature rise inside of the battery, which can produce fire after a certain level. The situation is further aggravated by the flammable nature of the electrolyte fluid. According to the creator (Yazhang Li) and his team, these dendrites are mostly formed while charging the batteries. Although it has been known so far, but the exact mechanism has remained hidden until now. The above mentioned cryo-EM, the scientists were given a new-opportunity to observe the process in a non-destructive method. Due to this device, it was discovered that the dendrites are arranged in monocrystalline, polished nanotube structures with a diameter from 100 nm to 2 μm, depending on the charge current. The growth of these dendrites will cause lifespan and performance decreasing, while the risk will be increasing.
The researchers aim are not only lead to a better understanding of the process, but also to the creation of safer batteries. They proved that lithium dendrites are organized into different nanostructures under different conditions. With this knowledge, the designers will able to effectively counteract the short circuits they caused. [11]

4. EXPLOSION OF LITHIUM-POLYMER BATTERIES

The lithium-polymer batteries are also rechargeable battery types. These are also called Li-ion batteries, because using lithium-ion technology, but at this case the material of the electrolyte is a high conductivity semisolid polymer. With these batteries a higher specific energy achievable than other types of Li-ion batteries. They developed in the 1970s. As made up from dry and solid polymer electrolyte, the developers created a battery with a thickness of a bank card, and an extremely good service life. Next to these advantages, they have a low weight and high security. Their disadvantage is the much higher cost than the Li-ion batteries Due to this fact, the Li-Po batteries are ideal for create the modern electrical vehicles.
When a Li-Po battery exploded, there is no flame, but this fact does not mean less danger. The heat produced by the Li-Po combustion is enough to ignite nearby objects. In the event of an explosion, one or more cells burst due to some effect, and the lithium inside the battery reacts with air. The degree of the reaction is proportional to the amount of electrical energy stored in the cell. The more charge is accumulated, the greater the response rate. This is powerfully true in case of Li-Po batteries because of the high specific energy. The failure of these type of batteries is the same that shown up previously: either physical impact or overcharging.

If the explosion occurs in a confined space, we need to provide some form of venting [12],[13].

5. ACCIDENTS

If the battery is overheated, barked or swollen, the battery should be removed immediately from flammable materials and placed on a non-combustible surface. The small lithium fires can be treated like any other fire: dust extinguishers, CO_2 extinguishers, ABC dry extinguisher, powdered graphite, copper powder or sodium carbonate extinguishers to prevent the spread of fire. If the amount of the lithium is small (for example a battery of an airplane) the fire extinguish can be carried out with water too. This water extinguish has another advantageous nature: the water will cool the adjacent cells, so the rate of the thermal runaway effect can be reduced or even stopped.
For larger fires water is no longer effective, because the water and the lithium are very reactive with each other. There is a solution, the copper enriched water could be effective, but this is expensive, and it is not necessarily available for firefighters. So, in case of a fire of electrical equipment or an EV, must use a D class fire extinguisher.
The phenomenon of thermal runaway effect can be reduced in the design phase. Since it is enough to damage only one cell to destroy the entire battery, should use these batteries in mounted battery packs, and these packs should contain inner insulations that can stop the runaway effect. All parts of the engine must be secured and the oil pan should be made of a material that is fire- and explosion-proof [14], [15].

Figure 2: Li-ion failure in a laptop

https://batteryuniversity.com/learn/article/safet
y
_concerns_with_li_ion

Figure 3: Li-ion failure in a smartphone

source:
https://www.howtogeek.com/338762/why-do-lithium-ion-batteries-explode/

Although lithium-based batteries are subjected to safety tests, nickel and lead-based batteries can cause fires. These are due to aging, rough handling and high temperature separator failures. Another method of protection is when a cooling medium flows around a cell or between more battery pack. These methods can be air cooling, refrigerant cooling, liquid cooling and cooling with phase change material (PCM). Some of them are used in commercial electric cars [16]–[18]. A very simple method when the cooling fluid flows in minichannels, which surround the battery packs. Xu et al. [19] made simulations about this cooling method, and according to their results that these minichannel cooling system could not prevent the thermal runaway in battery cells even a high cooling fluid flow rate is 10 L/min.

6. COMPARISON WITH OTHER ENERGY STORAGE DEVICES

It is important to be aware of the specific risk factor for lithium-ion batteries, but the risks should be considered in conjunction with other energy storage devices. Figure 4 shows relative energy densities as a function of energy storage devices. Compared to the fossil fuels it is clearly seen that Li-bases batteries have a much lower specific energy, which is more socially accepted.

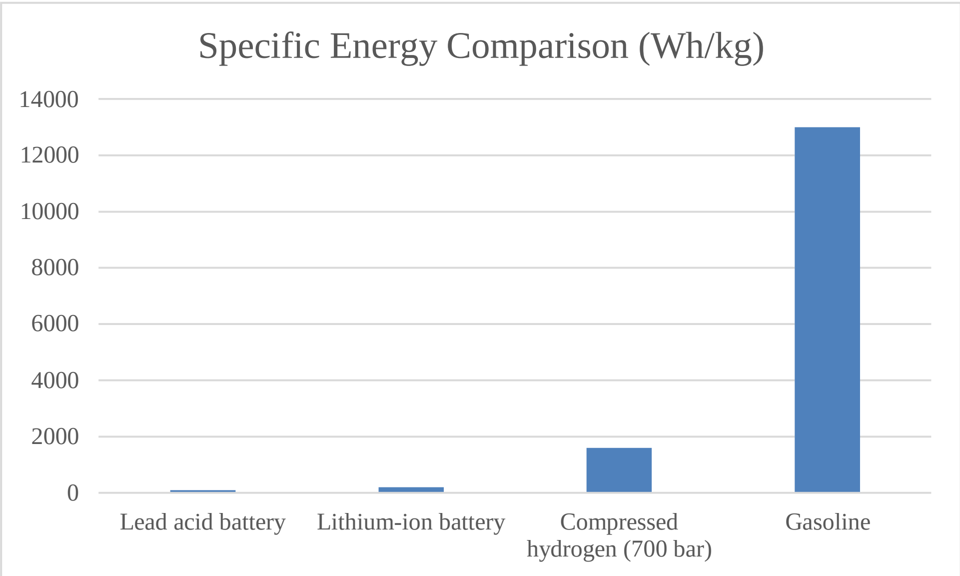

Figure 4: Comparison of the specific energies

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