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Electrical resistances of soldered battery cell connections

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ABSTRACT

Soldering has a high potential for electrically connecting single battery cells even for multicellular battery assemblies. This work evaluates soldered connections for battery cells by assessing the electrical connection resistance with a special measuring and calculation method. Due to the solder layer in between the joint partners, the current paths differ from welded connections. A resistance network and a finite element model (FEM) simulation are applied to understand these current paths. For the chosen test scenario, simulation predicts a reduction of the total connection resistance by the solder layer.

Measured connection resistances and tensile strength are compared to series of measurements with resistance spot welding, ultrasonic welding, laser beam welding and press connections. Not only the connection resistances are lower for soldered brass samples but also the tensile strength is higher.

For iron soldering on lithium-ion battery cells, the solder's liquidus temperature should be below ca. 150 °C. Other heating techniques, such as laser soldering, seem more promising, because the heat input is rapid and extremely localized.

As a conclusion, soldering is a good option for connecting battery cells. If the right heating technique is chosen and the parameters are optimally adjusted, soldering could overtrump other connection techniques in some aspects.

1. Introduction

The origin of soldering reaches back to around 3000 before Christ (BC) when the Mesopotamians joined copper pieces with lead solder [1,2]. Therefore, soldering is the oldest technique to build metallurgic bonds [1,2]. Nowadays, soldering is also used to electrically and mechanically connect battery cells. This technique to connect battery cells is often used by do-it-yourselfers or research institutions because the basic equipment for soldering is commercially available and relatively cheap, compared to welding techniques. But also for industrial productions, batteries are soldered as for example the battery modules of the full electric MINI E by the BMW AG [3].

In principal, soldering and brazing are based on a joining process where the joining partners are connected by melting and putting a filler metal, the solder, into the joint [1,2]. However, there are different types of flux, different types of solders, and various techniques for melting the solder. Although soldering is such an old technique and the principal is well known, there is a lot of innovation on this field, such as nanostructured solder foils [4]. Details on the functional principle of soldering are given in Section 2.

It is the focus of this work to investigate electrical connection resistances and ultimate tensile forces achieved by soldering. So, subsequent to the explanation of the basics of soldering, a measuring and calculation method to accurately determine the connection resistances of defined test samples is shortly presented in Section 3. This method has been presented in more detail in a previous publication [5].

The current paths and the resulting total connection resistances for soldered test samples are theoretically analyzed in Section 4. These considerations are more complex than for welding and have to be explained separately, because an additional metal, the solder, is added in between the joining partners.

Especially for lithium-ion battery cells, the heat input is a major criterion of connection techniques. So, in Section 5, the influence of different liquidus temperatures of solders on the connection resistance, the ultimate tensile force, and the heat input into battery cells of the 26,650 format is looked at in detail.

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Although soldering techniques have some significant advantages, welding techniques, such as spot and laser welding, are mostly used within the industrial production of batteries. In the penultimate section of this work, soldering is compared to welding techniques and press contacts in terms of electrical connection resistances and ultimate tensile force.

2. Basics on soldering techniques for battery assembly

Soldering and brazing techniques join metals by inserting and melting a filler metal, the solder, at the interfaces. Thereby, the melting temperature of the solder is well below, at least 50 °C below, the melting temperatures of the metals that have to be joined [1]. This is illustrated by Fig. 1 and results in the advantage that metals with different melting temperatures can be joined by soldering or brazing. By contrast, welding techniques require joint partners with similar melting temperatures and, theoretically, need more heat to melt the joint partners that show higher liquidus temperatures than a solder.

The process of soldering is illustrated by Fig. 2. Often a flux is used to obtain optimal soldering conditions. The flux removes the oxide layer on the surface of the metal joint partner and hinders air from the ambience to reach the metal surface [1,2] (see Fig. 2(a)). If the flux is compatible with the metal, a liquid drop of solder poured on the metal surface shows a wetting angle β of less than 90° [1,2] (see Fig. 2(b)). The bond between the solder and the metal joint partner is built by diffusion. Thereby, metal atoms of the solder diffuse into the metal joint partners and vice versa [1,2]. A diffusion area establishes and thereby the bond can be stronger than the bulk metal of the joint partners itself (see Fig. 2(c)) [6]. Results on the ultimate tensile force of joined metal test samples are presented later in Sections 5, 6, and 8.

According to the temperatures needed to melt the solder, the techniques based on this principle can be differentiated between soldering and brazing. As defined by the American Welding Society, soldering is done with solders that melt below 450 °C and brazing with solders melting above this temperature [7]. For battery cells the heat input of the connection process has to be relatively low to not damage the battery cell's internal electrochemical components. Accelerated rate calorimetry (ARC) on commercially available lithium-ion battery cells revealed that above 80 °C the solid electrolyte interface (SEI) or the electrolyte can be damaged [8,9]. So, in this work only soldering is considered, because lower temperatures are needed with soldering and therefore seems more suitable for connecting lithium-ion battery cells.

The heat input into the joint partners, for example the battery cell, mainly depends on the technique to melt the solder. The soldering techniques can be distinguished according to the following list. This list only comprises those techniques applicable to battery cells.

- **Iron soldering** is the most common heating technique used by do-it-yourselfers, researchers, and for prototyping. A soldering iron is pressed onto the solder and thereby transfers heat and melts the solder [10,11]. On the one hand, this technique is easy to handle and the equipment is highly available and relatively cheap. On the other hand, this technique does not provide rapid and localized heating and therefore also the temperature of a battery cell is likely to rise drastically.
- **Induction heating** is obtained by eddy currents that are induced into the joint by a coil [6,11]. The speed and the localized heat input into the joint partners are major advantages compared to iron soldering [10].
- **Resistance soldering** uses, similar to resistance spot welding, electric current that generates heat due to the electrical resistance of the joint [10]. The heat input can be controlled well and is localized at the joint [11] This technique does not depend on the accessibility of the joint and is suitable for connecting battery cells.
- **Laser** can be absorbed by the solder and thereby heat up and melt the solder as well [12]. Either the joint is directly accessible or the covering joint partner has to be pierced through, similar to keyhole welding. This method is also referred to as laser-braze welding [13]. In general, the advantage of laser heating is that it provides very rapid and extremely localized heating [10].
- **Reactive nanofoils** can serve as heat source for melting the solder. These foils are the solder material as well, that is melted by applying an electric spark [4]. The heating is very rapid and extremely localized and therefore can be applied to battery cells without damage.

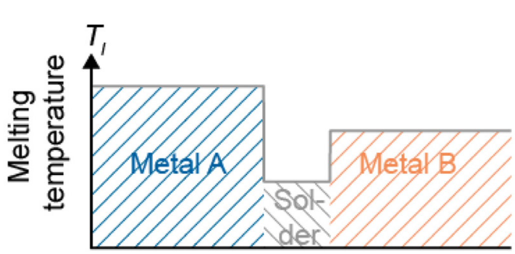

Fig. 1. Melting temperatures of metal joint partners and solder.

The heating technique is not crucial for the investigations and the comparison of soldered test samples in terms of electrical connection resistance and ultimate tensile force. So, within this work iron soldering was used, because it is easiest to handle. For connecting battery cells by iron soldering only solders with a low liquidus temperature are applicable.

3. Measuring and calculation method for electrical connection resistance of soldered connections

To obtain transferable results, the electrical connection resistance has to be determined and therefore a measuring and corresponding calculation method is presented in this section. The measuring and calculation method for a test sample with clearly defined dimensions was introduced in [5] to analyze welded connections.

As shown in Fig. 3, each test sample consists of two specimens with an overlap area that is used for soldering. The contact area is by default 15 mm × 15 mm. The height of each specimen h is 0.2 mm, the length l is 50 mm, the width b is 15 mm, and $l_{A0,B0}$, the distance of the overlap from point A_0 to B_0, is also 15 mm.

For the ideal electrical connection, the electrical contact resistance would be zero. For this ideal case, the resistance of the overlap $R_{A0,B0,id}$ can be calculated by Eq. (1).

$$R_{A0,B0,id} = (\rho_A \cdot l_{A0,B0}/h \cdot b))||(\rho_B \cdot l_{A0,B0}/h \cdot b)) \quad (1)$$

The material electrical resistivity of the specimens A and B are denoted by ρ_A and ρ_B and have to be known for the series of measurements and the calculation method presented within this work.

By measuring the resistances from each of the points A_1, A_2, or A_3 to each of the points B_1, B_2, or B_3 the electrical resistance of the overlap $R_{A0,B0,meas}$ can be calculated. Finally, the difference between the measured resistance $R_{A0,B0,meas}$ and the ideal resistance $R_{A0,B0,id}$ is calculated and denoted as electrical connection resistance R_C.

$$R_C = R_{A0,B0,meas} - R_{A0,B0,id} \quad (2)$$