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Cell Interconnections in Battery Packs Using Laser-assisted Ultrasonic Wire Bonding

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Abstract

This paper presents the results of a series of bonding tests using a laser-assisted ultrasonic wire bonding process. Aluminium and copper wire, both 500 µm (20 mil) thick, were bonded to nickel-coated steel caps of type 21700 battery cells. Mechanical bond strength tests prove that laser-assisted wire bonding has significant advantages over room temperature wire bonding. For example, it can be used to reduce the process time with aluminium wire or to increase the bondability of copper wire on nickel-coated steel. The results show a direct relation between tool tip temperature and measured bond strength. The quality of the joints was effectively improved by heating the tool tip up to 430 °C. These advantages are the same as in classic thermosonic wire bonding, but without the major disadvantage of having to heat to whole package. The cell temperature was shown to remain safely below the critical 60 °C in any application.

Key words

Battery pack manufacturing, thermosonic bonding, laser heating, tool heating, wire bonding, Aluminium wire, Copper wire

I. Introduction

Automotive battery packs for electric vehicles typically consist of hundreds of cells, appropriately interconnected to provide the voltage and current levels required for driving. These interconnections must not only fulfil tight electrical specifications, but also be robust to withstand mechanical and thermomechanical operational stresses, caused e.g. by vibrations, ambient temperature and self-heating of the cells. The challenges related to the joining of battery cells partly depend on the employed cell type. This paper focusses on cylindrical cells as used by several major automotive companies, where the challenges lie in dissimilar materials with high heat conductance and the demand for high throughput and precision. Today, various joining techniques are used industrially, such as resistance welding, laser welding, ultrasonic welding, and ultrasonic wire bonding [1].

Resistance welding of the joining partners is achieved by Joule heating caused by an electric current flowing through the joining point. The current is provided by two electrodes. The primary disadvantage of resistance welding is that it cannot be used properly with electrically advantageous high conductance materials like copper, as Joule heat depends on resistance and heat is quickly conducted away from the joining point. Laser welding is an alternative which offers process advantages regarding speed and flexibility compared to resistance welding. Here, the joining point is locally heated and melted with a high-power laser beam, fast enough to join even copper. But laser welding also has some disadvantages. The process must be adjusted and controlled very precisely in order to obtain constant quality, zero gap between the joining partners must be ensured. Laser melting usually produces undesired metal splashes in the surrounding area. Also, the process environment must be protected from reflected or scattered laser radiation. A high laser power must be provided, since the absorption of relevant metals at infrared wavelengths, which are available in robust and economic high-power lasers, is very low. Higher absorption is reached at shorter wavelengths, but such lasers are expensive and less reliable. Resistance welding and laser welding both melt the joining partners and thus share the drawback that melting and solidifying leads to considerable surface tensions and a significant heat affected zone in which the metal structure is changed.

Considering key factors such as process reliability, ease of use, and cost, ultrasonic welding has become a widely used joining technique for battery pack assembly due to its ability to join dissimilar metals, such as aluminium to copper, in an automated process at relatively low cost [2]. Ultrasonic welding is a solid-state joining technique that connects two metallic partners without melting. High frequency vibration under moderate clamping forces causes relative movement between the partners. This initiates a friction welding process, driven by interdiffusion and formation of intermetallic compounds. Ultrasonic wire bonding is a technologically related ultrasonic joining technique for low and medium power connections, in which the connector material (round wire or ribbon) is provided within the process. However, there are several significant differences between typical equipment for ultrasonic welding and ultrasonic wire bonding. Ultrasonic metal welding equipment typically has a stationary ultrasound transducer. The product must be placed underneath it to be welded. The welding tool tip must be large enough to cover all manufacturing and placement tolerances and sufficient space must be provided in product design. Automatic wire bonding machines can move and rotate the ultrasound transducer very precisely and provide image recognition to detect the exact bond location and derive an optimal trajectory to reach the desired position quickly and very precisely. This allows very tight spacing and thus compact and economic products. Recently, equipment has been presented which aims at combining the advantages of the two types of ultrasonic joining equipment [3].

As the requirements for battery pack joining have increasingly converged with typical wire bonding requirements, ultrasonic wire bonding has become a feasible alternative for such applications. It is successfully used mainly with aluminium wires with a diameter up to 500 µm. Much larger diameters have not been possible to date due to power limitations of available bonding equipment. For example, Tesla Model S uses 375 µm (15 mil) Al wires as interconnects between its 18650 Li-ion battery cells and the bus plate [4].

As a wire material, copper has some relevant advantages over aluminium, proven in power electronics applications [5-7]. Because of the differing material properties, the bonding parameters in copper wire bonding differ significantly from those of aluminium wire bonding. Most significantly, ultrasonic power and normal force are higher. In battery pack applications, normal force and/or vibration amplitude are limited by the sensitivity of the battery isolator ring; the cell surfaces to be connected are typically nickel-coated steel. Until now, it was neither possible to reliably bond copper wire under these circumstances nor reach the required process times for industrial battery pack assembly. Similar constraints must also be met in power electronics applications, where too high force and/or vibration amplitude can damage the die.

An effective solution to this joining problem is to provide additional thermal energy during the bonding process. Heating of the whole battery pack is impractical, as Li-ion battery cells can only withstand a limited temperature of about 60 °C. Instead, the new technique of laser-assisted thermosonic wire bonding [8, 9] is investigated. This technique uses a near infrared laser source integrated into the bonding setup. The laser radiation is used to heat the tool tip during or immediately before the bonding process. Wire and connection area are heated by heat conductance from the hot tool tip. The temperature is controlled by pyrometry to keep the bonding quality constant. This approach provides heat locally and only during the process without affecting surrounding materials. On test substrates, this technique enables bonds equivalent in strength to standard (room temperature) ultrasonic wire bonds, but with reduced force and/or bonding time [8, 9]. Investigating its potential on cylindrical battery cells is the subject of this investigation.

II. Test Setup

The test setup is based on a Hesse Mechatronics Bondjet BJ959 automatic wire bonding machine equipped with a near infrared (IR-A) laser, which is focussed onto the tip of a special bonding tool for 500 µm, as described in [9]. The temperature of the tool tip is measured and controlled by adjusting the laser power. This ensures a constant tip temperature, which is a prerequisite for a consistent bond quality. The tool material has an absorption rate of approximately 70 % at IR-A wavelengths, much more than the < 5 % of standard wire materials like copper. This dramatically increases the share of the laser power usable in the process and, together with a “beam trap” tool tip design, ensures that all of the laser power is used for heating the tool tip. Thus, laser sources of relatively low power can be used.

All tests in this paper were performed with equal bonding tools for 500 µm wires on passive cylindrical (“dummy”) cells of size 21700 (21 mm diameter, 70 mm height). Tests were only carried out on the positive terminals of the cells.

In preliminary tests, single bonds were arranged on the cell cap in two circles with one additional bond in the centre as shown in Figure 1. Bonds on the outer ring showed relatively large variation because of the highly position-dependent mechanical support of the cap, which in this case is supported with three joints. Only one bond can be placed in the centre of the cell. The best compromise between variation and number of bonds per cell was found in the inner ring, highlighted in red in Figure 1. It allows eight bonds per cell with little position-dependence of the bond strength. Such bonds are investigated in the following.

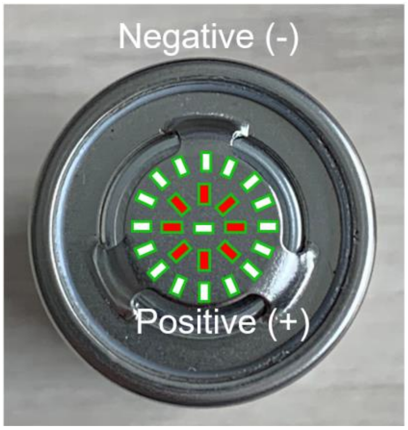


Figure 1: Test setup with dummy cell type 21700 and bond positions

III. Test Results

A. Aluminium wire

500 µm aluminium wire (Heraeus AL-H11) was bonded with parameter set 1, using a current pre-setting and a total length of 520 ms, of which the last 400 ms use constant force and current. First, bonds were produced at room temperature to determine the reference process without a heated tool. Decreasing the process time (by shortening the phase of constant force and current) decreases the shear force in all investigated cases. Such a variation of bonding time is documented in Figure 2. At a process time of 120 ms, no successful bonding (shear force 0 cN) between wire and cap was observed anymore.

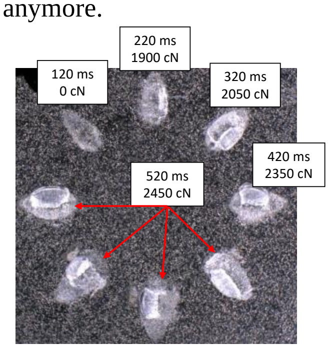


Figure 2: Shear test residues of Al bonds on a battery cap of nickel-coated steel, made at room temperature with parameter set 1 using varied process times and their (mean) shear force.

Bonds created with a bonding time of 520 ms without additional heat were repeated for a full inner circle (see Figure 3) on two caps. The mean shear force of these 16 single bonds was 2273 cN with a sample standard deviation of 112 cN.

Figure 3: Al bonds and their shear test residues on a battery cap of nickel-coated steel, made at room temperature with parameter set 1 (length 520 ms)

To determine the time saving potential of laser assisted wire bonding, parameter set 1 was combined with a tool tip heated to 430 °C. The bonding results are visually the same as with room temperature bonding, cf. Figure 6 and Figure 5. 16 single bonds created at 430 °C with a drastically shortened parameter set 1 (150 ms) show an even slightly higher mean shear force of 2546 cN (sample standard deviation 189 cN) than bonds created with parameter set 1 at room temperature with 520 ms. Figure 5 shows the resulting shear residues.

Figure 4: Al bonds and their shear test residues on a battery cap of nickel-coated steel, made with shortened parameter set 1 (length 150 ms) with the bonding tool at 430°

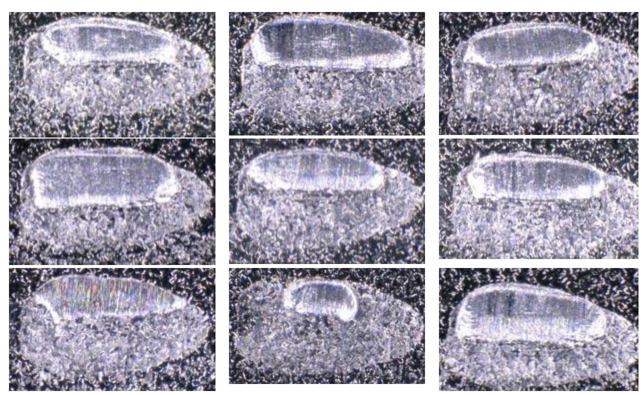
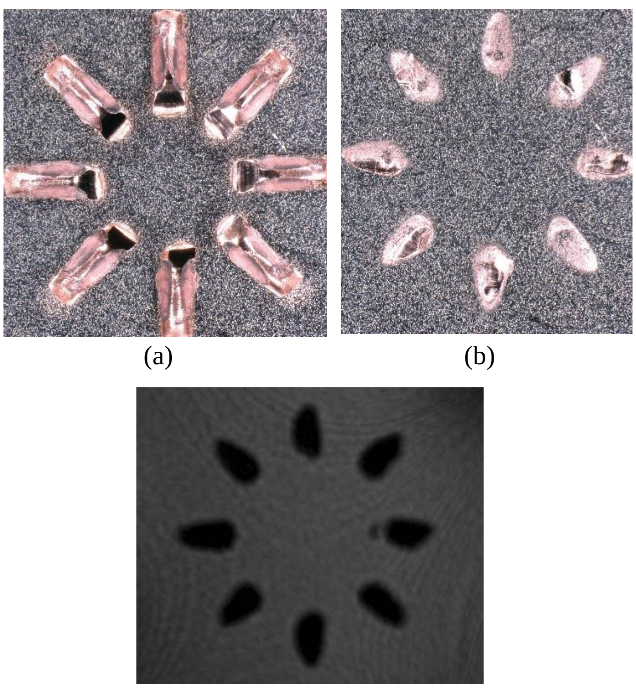


Figure 5: Shear test residues of Al bonds produced on a battery cap of nickel-coated steel with shortened parameter set 1 (length 150 ms) with the bonding tool at 430 °C

B. *Copper wire*

Literature [9] and the previous tests with aluminium wire show that heating the tool to 430 °C allows a significant reduction of the bonding time. In this section, this is also examined for 500 µm copper wire (Heraeus PowerCu Soft). As in the aluminium wire tests, single bonds were bonded to the cap, in the inner circle as shown in Figure 1. No reliable results were achieved at room temperature. Satisfactory results are only achieved with the addition of heat. Parameter set 2 is used for bonding copper at a tool tip temperature of 430 °C. The average normal force (115 % of parameter set 1) and especially the ultrasonic current (325 % of parameter set 1) are higher than those used for aluminium wire, while the bonding times are very similar with 175 ms (Cu) resp. 150 ms (Al). This indicates that the aluminium wires could probably be bonded in even shorter time, if the parameters were further optimized.

The mean shear force of the 16 single bonds is 6474 cN with a sample standard deviation of 613 cN. Figure 6 (a-b) shows 8 of these examined bonds. Ultrasonic microscopy indicates that wires and cap are properly bonded (see Figure 6 (c)).



(a) (b) (c)

Figure 6: Cu bonds (a), their shear test residues (b), and Ultrasonic microscopy image of the bond interfaces (c) on a battery cap of nickel-coated steel, made with parameter set 2 with the bonding tool at 430 °C

Bonding connections formed with these parameters were also analysed using a pull test. Figure 7 shows such a copper wire connection before and after the test. Average pull values of 6668 cN at a sample standard deviation of 499 cN are reached for a sample size of 8 connections. Joints between two supports (left in Figure 7(a)) show a high strength variation. Joints next to a support (right in Figure 7(a)) show a high strength with only heel breaks and wire breaks.

(a) (b)

Figure 7: Cu on a battery cap of nickel-coated steel before (a) and after pull test with wire break at 7159 cN (b)

Cell manufacturers usually define 60 °C as the maximal temperature of the whole battery. To ensure that this temperature is not reached using the laser-assisted bonding process, even under the worst circumstances, a test was performed with the aim to heat the cap as much as possible: The previously used bond programme was modified to bond a sequence of nine bonds on one cap (half of the outer circle in Figure 1) three times in a row. To allow this, no ultrasound was applied, thus no bond was formed. The process time, i.e. the contact time between wire and cap, was increased by a factor of 4. A single point thermal resistance sensor, placed at the centre of the cap, was used for temperature measurement. The measured local temperature is shown in Figure 8. The tests were carried out with wire (red line) and without wire (green line) between tool and cap. Heating of the cap during repeated "bonding" can be observed as well as cooling during the shorter and longer phases without tool touchdown.

The temperature measured after bonding with wire is approximately 10 °C higher compared to when only the tool has touched the cap. The dominant reason for this is that the plastically deforming, relatively soft, high-conductance wire provides much better heat conduction between tool and cap than the small direct contact between the hard tool and the cap. The highest observed temperature is approx. 60 °C. In a real application such as battery pack manufacturing, this value will never be reached, even with extremely long process times as in this test. Such applications will not include ten or more wires on a single cell, and significant additional time is needed for looping the wires to the bus bars, during which the cell can cool down.

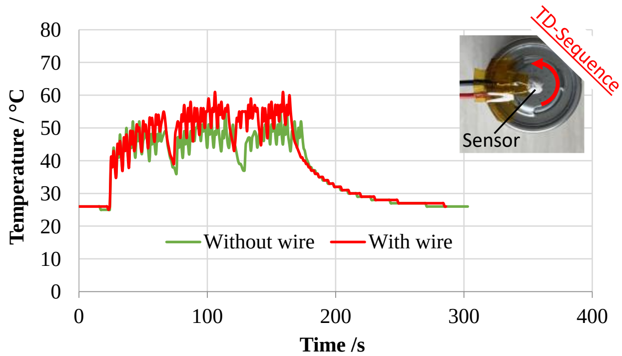


Figure 8: Single point temperature measurement on the cap

Finally, an application-oriented example is shown in Figure 9. The pack uses 4 x 6 cells of type 21700 in a 6p4s configuration (6 cells in parallel, 4 in series), resulting in a pack voltage of 4 x 3.6 V = 14.4 V if real cells were used. It was developed by Hesse Mechatronics for demonstration purposes. Copper wire is used, and the bus bars between the cells are also made of copper. The time needed for bonding the complete pack, which includes a total of 78 bonds, using 500 µm copper wire is about 28 seconds. This is significantly shorter even than the 34,8 s conservatively estimated for aluminium wire bonding of the same module [3], which shows that process time comparisons should be based on real, optimized joining processes.

Figure 9: Detail of battery pack produced with copper wire

IV. Conclusion

The bond test results presented above prove that laser-assisted wire bonding with a heated tool has a significant advantage on battery cells. It can either be used to reduce the process time bonding aluminium or to increase the bondability of copper wire on nickel-coated steel cells. Destructive tests with shear and pull testing machines were made. In all investigated cases, laser-heated bonding connections were better than conventional bonding connections. Ultrasonic microscopy showed excellent bonded areas in in the interface between wire and cap. Temperature measurements using a thermal resistance sensor showed that the heated tool has only a small effect on the overall temperature of the cap and that cell temperature safely remains below the critical 60 °C. Laser-assisted thermosonic wire bonding thus enables advanced bonding of cylindrical battery cells for the next generation of battery packs and related applications.

References

[1] Das, A.; Li, D.; Williams, D.; Greenwood, D.: *Joining Technologies for Automotive Battery Systems Manufacturing*. World Electr. Veh. J., 2018, 9, 22. DOI:10.3390/wevj9020022

[2] Kang, B.; Cai, W.; and Ta, Chin-An: *Dynamic response of battery tabs under ultrasonic welding*. Journal of Manufacturing Science and Engineering 135.5 (2013): 051013. DOI:10.1115/1.4024535

[3] Hunstig, M.; Schaermann, W.; Brökelmann, M.; Holtkämper, S.; Siepe, D.; Hesse, Hans J.: *Smart Ultrasonic Welding in Power Electronics Packaging*. Int. Conf. on Integrated Power Electronics Systems (CIPS), Berlin, Germany, 2020

[4] Cai, W. W.: Ultrasonic Welding of Lithium-Ion Batteries. ASME Press, 2017. DOI:10.1115/1.861257

[5] Siepe, D., Bayerer, R., Roth, R.: *The future of wire bonding is? Wire bonding!*, Int. Conf. on Integrated Power Electronics Systems (CIPS), Nuremberg, Germany, 2010

[6] Guth, K.; Siepe, D.; Görlich, J.; Torwesten, H.; Roth, R.; Hille, F.; Umbach, F.: *New assembly and interconnects beyond sintering methods*, PCIM Europe 2010, pp. 219-224

[7] Brökelmann, M.; Siepe, D.; Hunstig, M.; McKeown, M.; Oftebro, K.: *Copper wire bonding ready for industrial mass production*. 48th Int. Symp. on Microelectronics (IMAPS), Orlando (FL), USA, Oct. 26-29, 2015. DOI:10.4071/isom-2015-WP32

[8] Unger, A.; Hunstig, M.; Brökelmann, M.; Hesse, H. J.: *Thermosonic wedge-wedge bonding using dosed tool heating*. European Microelectronics and Packaging Conf. (EMPC), Pisa, Italy, September 16-19, 2019. DOI:10.23919/EMPC44848.2019.8951825

[9] Hunstig, M.; Unger, A.; Brökelmann, M.; Hesse, H. J.: *Process advantages of thermosonic wedge-wedge bonding using dosed tool heating*. 52nd Int. Symp. on Microelectronics (IMAPS), Boston (MA), USA, October 1-3, 2019. DOI:10.4071/2380-4505-2019.1.000519