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Electrical performance of laser braze-welded aluminum–copper interconnects

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ABSTRACT

The reported investigation is related to laser beam braze-welding technology for dissimilar aluminum–copper interconnects for Li-ion battery assembly. The correlation between the brittle and high-resistivity intermetallic compounds and the electrical contact resistance showed that a thin intermetallic layer is highly desirable. It was proved that highest shear strength and lowest contact resistance can be achieved within the same parameter set which is of particular interest to battery electrical vehicle applications requiring both high mechanical reliability and electrical performance.

A study on the weld seam layout further showed that two parallel weld seams with optimized spacing and overlap design provide lowest contact resistance.

1. Introduction

Lithium-ion batteries are key components in the pursuit of high performance energy storage for electric vehicles. Their good volumetric power and energy density and the high open-circuit voltage are the main advantages compared to other battery types, e.g. NiMH cells [1].

Prismatic cells are increasingly replaced by pouch cells, even in space applications [2], which are characterized by a thin housing and two flat connection terminals typically made of aluminum and copper.

Several cells are combined into battery modules which usually include monitoring electronics to track the state of health and state of charge of each cell. A number of battery modules are assembled to the traction battery pack designed specifically to meet the geometry requirements of the vehicle [3]. For the battery module assembly, cell-to-cell as well as cell-to-busbar joining operations are required. Hence, Al–Al and Cu–Cu joining for parallel connections, and dissimilar materials Al–Cu joining for serial joining have to be made, see Fig. 1. The gauge of the battery terminals is typically 0.2 mm, the gauge of the bus bars ranges from 0.5 to 1.0 mm.

A battery pack for electric (EV) or hybrid electric vehicles (HEV) consists of hundreds of individual battery cells. Thus, a reliable and robust joining process is mandatory for the large number of joining operations per vehicle. In addition to good static and fatigue strength, excellent electrical contact resistance is crucial for battery connections since the power loss at each joint is directly proportional to the contact resistance which can be calculated by $P_{\text{loss}} = R_{\text{contact}} \times I^2$.

The commonly used mechanical fastening with bolts and nuts provides for easy disassembly but adds extra parts with added cost and mass. Mechanical fastening, however, has a distinctive disadvantage: the form locking mechanism between the mating parts leads to a small effective conducting area, so called a-spots, caused by the roughness of the surface [4]. It is estimated that the contact resistance for this case can be expressed as:

$$R_{\text{contact}} = \frac{\rho}{2a} + \frac{\sigma}{\pi a^2} \quad (1)$$

where ρ is the contact resistivity, a the radius of the surface-to-surface contact area and σ the resistance per area of oxide, sulfide or other inorganic films which are generally present on metal surfaces.

Thus, fusion welding processes are desirable, providing full bonding between both parts. Only minor bonding defects would cause imperfections and increase the resistance.

Besides ultrasonic welding [5,6], friction stir welding [7] and roll-plating [8], many research efforts have been made in the area of laser beam welding. Laser light has the advantage of high power density and excellent controllability which enables welding of dissimilar material combinations [9–12].

During the fusion welding process, materials are mixed and consequently alloyed. In the Al–Cu binary system, several intermetallic compounds (IMC) are formed which are characterized by

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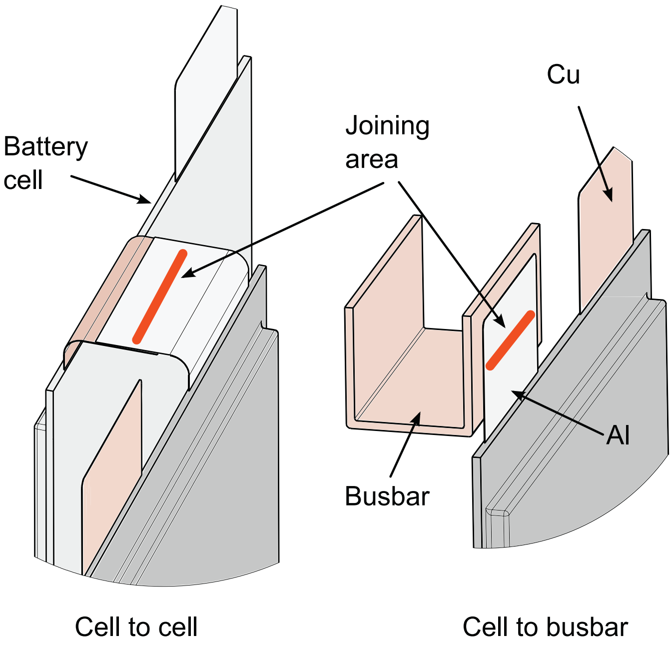

Fig. 1. Battery-to-battery and battery-to-bus bar interconnections.

brittleness, high hardness [13] and high specific electrical resistance up to six times higher than the materials Al and Cu, see Table 1 [13,14].

Braunovic [4] proved that an Al–Cu interface behaves highly brittle when the intermetallic layer exceeds a thickness of 2–5 μm. Below this critical thickness, a ductile behavior was observed. Furthermore, the interface conductivity increases strongly with decreasing thickness of the intermetallics [8].

Thus, the intermetallic compound layers must be as thin as possible to provide high strength and low electrical resistance.

In addition to the metallurgical factors for best electrical performance, the weld seam design must be taken into account. Schmidt et al. [12] investigated different seam patterns for laser beam welding in the deep welding mode with and without beam oscillation where high variations of the electrical resistance were observed. So far, few publications exist addressing the effect of the weld seam layout on the electrical characteristics.

This paper reports our recent work on the electrical properties of laser braze-welded Al–Cu joints. The main focus of the work was on:

- The effect of intermetallic compounds on the contact electrical resistance of an aluminum–copper joint,
- The correlation between mechanical and electrical properties of the joint and
- The impact of the weld seam layout on the contact electrical resistance.

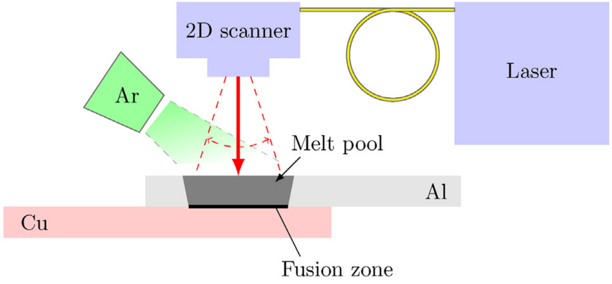

Fig. 2. Laser setup.

2. The laser beam braze-welding process

2.1. Process fundamentals

Aluminum and copper are configured in overlap for the joining task. A laser beam irradiates the aluminum surface and melts the aluminum specimen. Copper remains in solid state during the process. The molten aluminum wets the copper surface and the diffusion process between both materials is initiated, see Fig. 2.

Due to the low Fresnel absorption of infrared light on the aluminum surface and the high thermal conductivity of both aluminum and copper [15], keyhole mode welding is better suited than conduction mode welding. The resulting very short process time limits the duration of the molten pool distinctively. Thus, diffusion between aluminum and copper can be reduced to a minimum.

To provide a stable keyhole in the aluminum layer, a small beam diameter is chosen for high intensity on the aluminum surface with a related high aspect ratio between welding depth and width. In addition, a circular spatial power modulation is superposed to the feed direction in order to enlarge the interface width and to tailor the heat input into the joint zone.

The trajectory of the superposed movement can be described according to Eq. (2):

$$\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} -a\cos(2\pi ft) + vt + a_0 \\ -a\sin(2\pi ft) \end{pmatrix} \tag{2}$$

with f (Hz) the scanning frequency; a (mm) the amplitude of circular movement; a_0 (mm) the starting value for a, here: $a_0 = 0$; v (mm s^{-1}) the feed rate in x-direction.

The overlap n in x-direction between two cycles at $y = 0$ can be defined to

$$n = \frac{x(T/2) - x(2T)}{x(T/2) - x(T)} = \frac{4 \cdot a - 3 \cdot v/f}{4 \cdot a - (v/f)}. \tag{3}$$

From [16] it is known that good interface quality can be achieved with $a = 0.25$ mm and $n = 0.75$ at $f = 500$ Hz.

To adapt the process to different gauge combinations of the specimens, the laser power can be reduced by temporal power modulation. This has the advantage of taking over the spatial parameters a and n, see Eqs. (2) and (3), which provide a homogenous interface. Temporal power modulation has been chosen to

Table 1
Selected intermetallic compounds in the Al–Cu system [13,14].

Phase	Composition	Crystal structure	Atoms per unit cell	Hardness HV (10 g)	Specific resistance (μΩ cm)
Cu	100% Cu	Face-centered cubic	12 Cu	75	2.0
γ_2	Al_4Cu_9	Body-centered cubic	36 Cu, 16 Al	770	14.2
ζ_2	Al_3Cu_4	Monoclinic	12 Cu, 9 Al	930	12.2
η_2	AlCu	Body-centered orthorhombic	10 Cu, 10 Al	905	11.4
θ	Al_2Cu	Body-centered tetragonal	4 Cu, 8 Al	630	8.0
Al	100% Al	Face-centered cubic	12 Al	36	2.4