

Process Robustness of Laser Braze-Welded Al/Cu Connectors

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ABSTRACT

Laser welding of dissimilar metals such as Aluminum and Copper, which is required for Li-ion battery joining, is challenging due to the inevitable formation of the brittle and high electrical-resistant intermetallic compounds. Recent research has shown that by using a novel technology, called laser braze-welding, the Al-Cu intermetallics can be minimized to achieve superior mechanical and electrical joint performance. This paper investigates the robustness of the laser braze-welding process. Three product and process categories, i.e. choice of materials, joint configurations, and process conditions, are studied. It is found that in-process effects such as sample cleanliness and shielding gas fluctuations have a minor influence on the process robustness. Furthermore, many pre-process effects, e.g. design changes such as multiple layers or anodized base material can be successfully welded by process adaptation. The minimization of the interface gap is identified as the most significant influence of process stability. The specimen were validated by mechanical lap shear tests and metallographic analysis.

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INTRODUCTION

The development of sustainable and energy-efficient electric drive vehicles is considered the key challenge for future automotive industry. The performance of new electric vehicles depends on the power and capacity of the energy storage. Hence, the manufacturing of battery assemblies is one competitive technology for the deployment of electric cars.

Today, battery pack assemblies consist of hundreds to thousands of battery cells which need to be joined robustly and economically. For electrochemical reasons one cell consist of electrolyte, separator and two electrodes with unequal electronegativity. For Lithium-ion cells, the cells with highest energy density, the current collectors are usually aluminum and copper (see figure 1). The connectors between the electrodes are manufactured using various materials, e.g. Al or Cu. During assembly, various thickness and number of electrodes need to be joined for performance requirements and manufacturing efficiency [1].

Dissimilar materials are difficult to join due to their different physicochemical characteristics, e.g. Aluminum and Copper are considered as not weldable by conventional welding techniques. The fusion joining of Aluminum and Copper causes a seam between both materials, where binary alloys are formed. These Intermetallic Compounds (IMC) are usually brittle and have less shear strength properties and a low conductivity factor [2], e.g. the electric resistance of Al-Cu IMCs is about 8 times greater than the electric resistance of the base materials. There is a critical width of the IMC's

at which the connection still shows a ductile behavior and the losses in strength and conductivity are strongly reduced. According to [3], this width must be less than 2.5 microns.

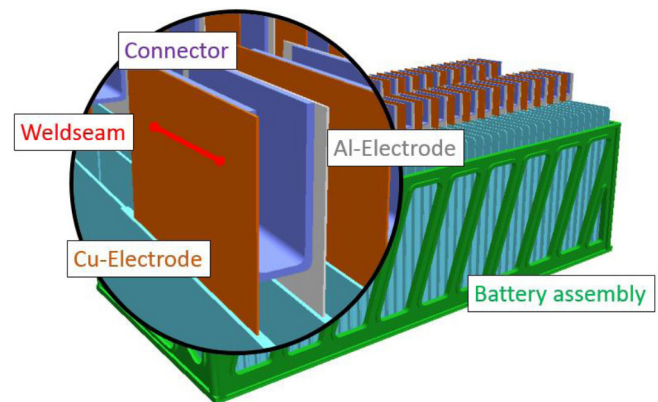


Figure 1. Battery assembly based on Li-ion cells with Cu and Al electrodes.

Existing joining techniques enable the production of those dissimilar connectors, e.g. ultrasonic welding [4] or frictions stir welding [5]. Current reviews of different joining techniques can be found in [6] and [1]. However, laser welding techniques are showing high potential for joining Aluminum and Copper [7 and 8]. Lasers are frequently used in high volume applications and offer high automation opportunity through its low inertia positioning system and contact less power delivery, as described by the authors in [2] and

[10]. Novel laser processing techniques control the energy input to reduce the interaction of the joining materials, whereby the IMC seam thickness is minimized [11, 12, 13 and 24].

Recent publications with the focus on laser welding of dissimilar Al-Cu Connectors were concentrated on optimizing the joining process on specific purposes, e.g. strength [7]. The authors in [14] enhance the ductility of the connections by using filler materials. In [15], the authors analyzed the effects of a tin foil as a filler material on laser joining of aluminum and copper. Other publications are focused on characterization of Al-Cu connectors [11, 12, 16 and 17] and the joint fracture behavior is analyzed [18].

This paper investigates the influence of external effects on the joining process performance. The resistance of the process to external disturbances is interpreted as process robustness. Different effects will be identified and analyzed to the laser welding process to prove the competitive manufacturing readiness of the process.

ORGANIZATION

During the investigations, dissimilar Al/Cu connectors were joined with defined pretreatments to analyze and evaluate the influence on the process robustness. The tests were chosen on expert experience based on preliminary investigations and on requirements from the industry.

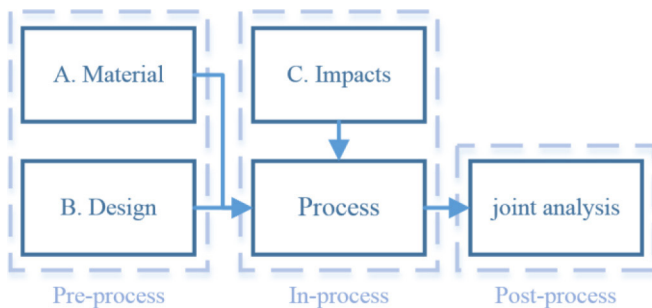


Figure 2. Structure of this paper.

The following structure was defined (see figure 2):

- A. Material effects
 1. Hardness
 2. Surface
- B. Design effects
 3. Multiple layers
 4. Coating
 5. Anodization
- C. Process effects
 6. Shielding gas
 7. Gap
 8. Cleanness

The material effects were linked to the base material properties and the design effects are usually requirements due to the product or manufacturing requirements. These effects were taken into account

before processing and cannot be influenced by the process. The direct process effects were grouped separately. The analysis of the weld performance was performed by post-process methods.

All tests will be performed by using the braze-welding process [10], which will be explained hereafter. The tests will deal with laser joining of Aluminum to Copper. A summary will point out the main advantages and issues on laser welding of Al-Cu connectors. The outlook will state opportunities to enhance the braze-welding process.

THE BRAZE-WELDING PRINCIPLE

The braze-welding process is based on the laser keyhole welding principle. The beam is focused on the material surface with an energy density of at least 1 MW/cm^2 [31], which melts and vaporizes the material. The vaporized metal forms a hole wherein the laser is reflected multiple times, thus the energy absorption of the metal is increased. This high energy input enables a fast process and a selective melting of the upper aluminum can be achieved, while the lower copper remains in solid state (see figure 3). Thus, the process is called a braze-welding process [24]. The realized fusion layer thickness between Al and Cu can be reduced to under $5 \mu\text{m}$. The formation of IMC is minimized, whereby a ductile metallic joint with reduced electric resistance is realized.

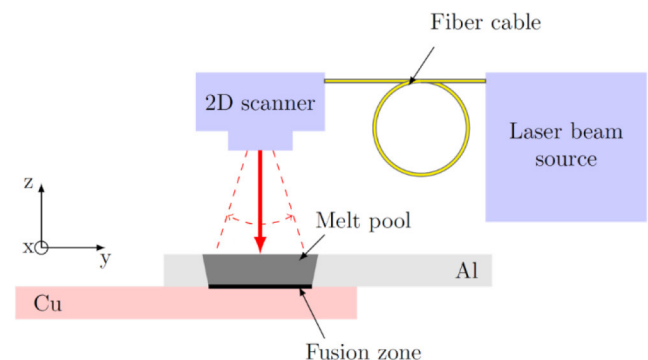


Figure 3. Braze welding process to join dissimilar metals [20].

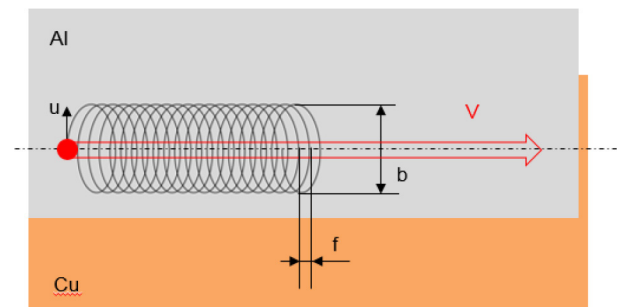


Figure 4. Spatial laser modulation to control weld seam width [7].

The mechanical properties of the joint depend on the surface area of the welded interface. The width of the interface is controlled by using a spatial power modulation [25] (figure 4), which furthermore can be used to define the weld pool geometry [12 and 26]. Current investigations have shown that high-frequency power oscillated laser-beam stabilize the welding process [27, 28 and 29] by reducing the penetration depth fluctuation and achieving a homogeneous heat

input. The author in [30] developed a guide for choosing process parameters for pulsed lasers for similar materials and analyzed their effect on heat flow, weld dimension and weldability.

METHODOLOGY

For the laser welding experiments, bare AA 1050/1100 and anodized AA 1145 were joined to SF/E-Cu. The coating and thickness changed depending on the test. The materials were always joined in overlap configuration. Each sample had a size of 40×40 mm with an overlap of 10 to 15 mm. The weld seam was welded with a length of 30 mm in the center of the overlap. The materials were joined without cleaning, except for tests in section C.8. The surface of the base material was dust and grease free, as well as uncrumpled. No shielding gas was used, except for tests in section C.6.

The laser machine applied in all the experiments was a Trumpf TruFiber 400 fiber laser machine with a wavelength of 1070 nm and a maximum power of 400 W. Taking into account the $31 \mu\text{m}$ spot diameter, a maximum power density of approximately 50 MW/cm^2 can be reached depending on the defocus setting. The spatial laser modulation was adapted to have a weld seam width of 0.5 mm and the temporal modulation was performed with a pulse frequency of 18 kHz. The pulse time was varied from 27 to $36 \mu\text{s}$ to control the energy input into the melt pool. The used parameters were developed during previous investigations [24]. They were optimized to enhance the mechanical durability and to minimize the IMC layer thickness. The laser path was controlled by a Scanlab HS20 2D scanner head.

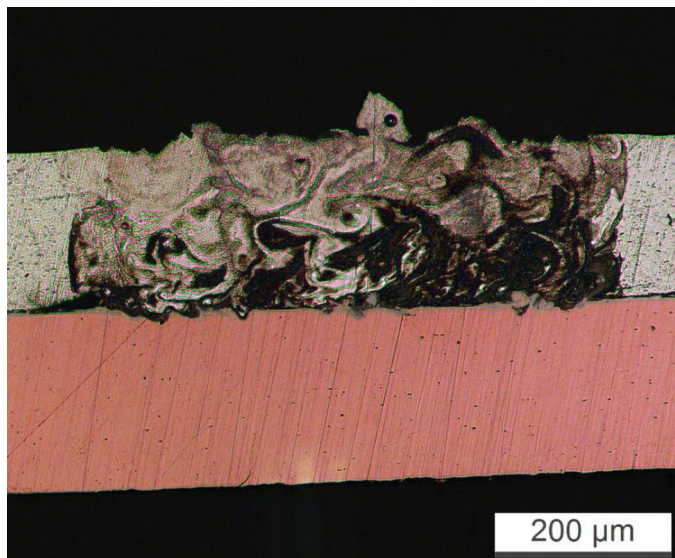


Figure 5. Exemplary cross section for a laser braze-welded dissimilar Al-Cu joint with reduced IMC layer thickness.

The weld seams were evaluated by performing mechanical and metallurgical tests. Cross-sectional micrographs were used to investigate the intermetallic interface, i.e. the layer thickness (see figure 5). Furthermore, the weld porosity and cracks could be evaluated. The samples were grinded with SiC-Paper up to roughness 1000. The samples were then polished with 6, 3 and $1 \mu\text{m}$ diamond

suspension. After cleaning with de-ionized water, the samples were etched with a Keller solution for 3 to 5 seconds. The cross sections were analyzed with an optical microscope using unpolarized light.

The mechanical performance was evaluated by a shear pull test by measuring the maximum shear force and the toughness of the joint. The tests were performed on a Zwick/Roell Z010 material testing machine with a pulling velocity of 3 mm/min and a sampling rate of 10 kHz. The toughness T can be calculated by:

$$T = \int_0^l F ds \quad (1)$$

With:

l : pulling distance upon failure

F : pulling force

s : strain

For a good joint quality, the maximum pulling force and toughness should be increased. Since the base material influences both factors, see chapter A.1, material control tests should be performed at the beginning of an investigation.

TESTS TO EVALUATE PROCESS ROBUSTNESS

A.1. Hardness

During the investigations it was found that the material hardness has an effect on the mechanical performance, particularly on the maximum pulling force. The influence of material properties on the process has also been reported by [14]. During the manufacturing process of the sheets, the metals were strain hardened, the strength is increased, but the total elongation is decreased [33]. Depending on the strain hardening history and heat-treatment, the metals can be divided in soft to hard in intermediate grades: annealed=soft; quarter hard; half hard; hard; etc. Figure 6 shows three Aluminum base material samples with different hardness.

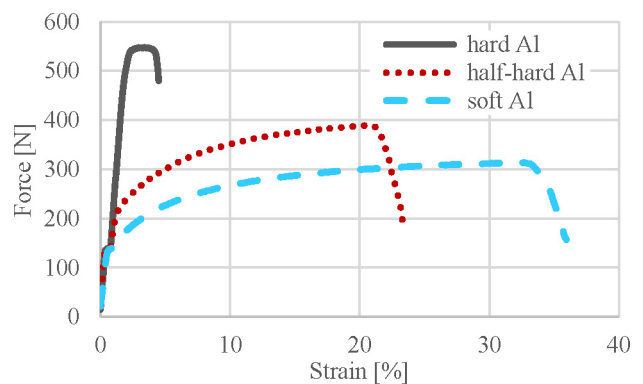


Figure 6. Pull tests results for Al base metal with different hardness.