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The challenge of welding mixed material. Strategies for joining copper and aluminum with a single mode laser

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Abstract

Joining of materials with dissimilar metallurgical properties constitutes a challenge in the context of modern battery production and e-mobility. Of particular importance for this application is to generate electrical connections with high conductance and high mechanical stability in a productive manner. We present advances in joining dissimilar materials such as copper and aluminum by implementing laser welding processes with a fast oscillating laser beam and high beam quality. This is of particular interest for high quality battery connections. The high beam quality enables a stable in-coupling into high reflective copper connectors with only little spatter formation. To achieve connections with high conductance an oscillation pattern is executed to create broad cross-sections, which are suitable for high current flows. To achieve mechanical stability, copper and aluminum are joined in a micro structured manner. At the same time the intermetallic phase created at the connection between copper and aluminum is minimized.

Keywords: *mixed material, copper, aluminum, oszillation welding, single mode laser, e-mobility, battery, cellconnector,*

1. Introduction

In this paper we present advances in strategies for joining dissimilar materials like copper and aluminum to realize battery connections by implementing distinct laser welding strategies with a fast oscillating single mode laser beam. Particularly important for this application is to generate electrical connections with high conductance and high mechanical stability in a productive manner. Laser scanning processes are well suited to meet productivity requirements since welding can be performed in a contactless manner, flexible and precise at high speed [Stritt, P. (2016)]. Methods to address joining of dissimilar metals involve pulsed lasers in the nanosecond time regime [Gabzdyl, J. (2017)], CW multimode lasers in the visible-range [Pantsar, H. (2019)] or CW single mode lasers in the NIR wavelength-range. In the current paper we focus on the last method, employing CW NIR single mode laser which by means of a fast oscillation of the laser beam enables a) wide surface connections for good conductance and mechanical stability, b) high penetration depth and, c) an excellent cost-performance ratio.

The main challenges to be faced when applying this method for joining dissimilar metals like Al and Cu are:

- The melting temperatures of Al and Cu differ by approximately 400 °K
- Al and Cu do not mix without intermetallic phases. Intermetallic phases are always brittle and reduce strength and conductivity

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- Spatters contaminate the cell connectors and the nearby components
- Long process time increases the heat input to sensitive battery cells, which thereby may reach damage level. On the same time distortion due to the heat load on the material reduces the fitting
- Heat accumulation changes penetration depth, resulting in non-uniform joints. The same applies to nonsymmetrical heat conduction into the fixture.

To demonstrate the method and how the above-mentioned challenges can be mastered, we present herewith distinct welding strategies and examples for joining Al and Cu metal plates at different overlap combinations, while having the Cu plate as upper element constitutes the most challenging case.

2. Laser equipment and setup

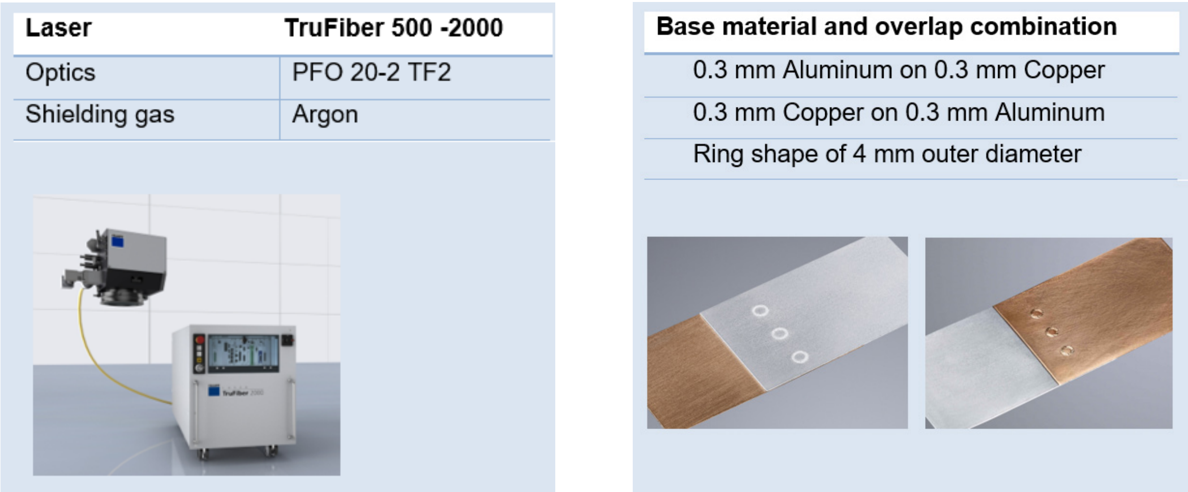

Fig. 1. Laser, optical setup and workpiece combinations

The new generation of single mode fiber laser "TruFiber" was employed as laser source, the nominal power of which was 2 kW. For low spattering, the laser power was adapted to the application. The laser is equipped with a scanning optical head "PFO 20-2" and software "TruTops PFO" to generate the scanning geometries. In order to evaluate the quality of the joint connection between the dissimilar metals, the following methods have been applied: High speed camera recordings; Microscopic and SEM imaging of the cross-sections; Tensile strength and cross tension tests [EN ISO 14272(2016)]; 4-point probe conductance test; Distance evaluation of damage temperatures.

3. Results

3.1. Beam quality and spot size

Due to the high reflectivity of the base materials Cu and Al it is essential to focus the laser beam to a small spot on the work piece. With the high-power densities inside this laser spot, the melting temperature of the base material is reached very fast. Absorption of laser power increases with temperature for Al and for Cu [Amorosi, S. (2003); Hügel, H. (2014)]. Multiple reflections in the keyhole in combination with high aspect ratio of the keyhole enhance the absorption effect drastically. This results in a very efficient and stable coupling of the laser power into the material. Single-mode beam quality is essential to fulfill this requirement, since for laser scanning applications the small spot size needs to be realized at large working distances. For the application presented in this paper a spot diameter on the work piece of approximately 40 µm at a working distance of 160 mm was realized in combination with the beam quality of M^2: 1.2.

3.2. Joining Al on Cu with wobble welding

In fig. 2. the results following an optimized strategy for joining Al on Cu are depicted. The welding strategy and process parameters have been chosen such as to nearly eliminate spatters which were counted by high speed camera imaging. The best scanning pattern for welding Al99.5 was a zig-zag geometry. Pores can be reduced to a very small amount respectively close to zero due to the stirring in the melt pool. This is verified by cross-section images.

The applied laser power was set to 250W, by which the penetration depth of the weld reached slightly below the interface between Al and Cu plates. The process time for welding of a single ring was 0.38 sec. More laser power combined with higher feed rates will reduce process time if lower quality (spatters, surface quality) is acceptable. A gentle laser power ramp was implemented to avoid spatters during establishing the keyhole at start and also at the end of the weld seam to generate a soft keyhole closing. It needs to be noted that this welding strategy shows a comfortable process window: ±60 W for laser power and ±1 mm for z-position.

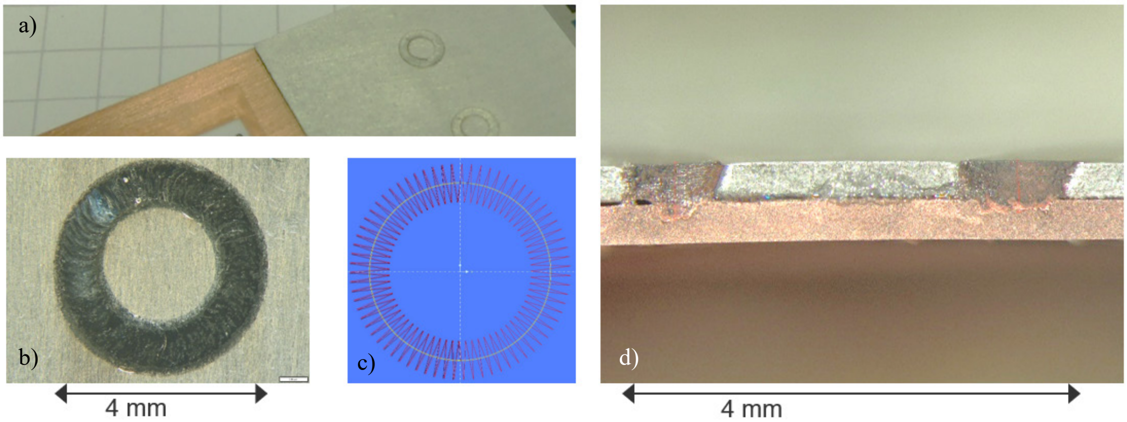

Fig. 2. Wobble welding of Al on Cu a) b) overview and detail of welding from top side c) wobble geometry d) cross section through ring center

3.3. *Joining Cu on Al with hatch welding*

A most challenging combination in joining dissimilar materials is given when the upper metal plate comprises much higher melting temperature than the lower one like in the sample depicted in fig. 3. In this case the use of the welding strategy described in 3.2 led to burning through the underlying Al plate. To avoid this, the scanning pattern depicted in fig. 3.c) was employed. This pattern consists of nine concentric rings, which are scanned nonstop (like a spiral). After scanning all nine rings a second pass over the same trajectory was scanned in order to generate a stable connection between Cu and Al. This pattern creates a weld that has very good mechanical and electrical properties. TRUMPF has a patent pending filed on this strategy.

For this welding strategy 520 W of laser power were used, while the process time for both passes through the scanning pattern was approximately 0.5 sec. In this case the process window is significantly reduced: ±20 W for laser power and ±0,25 mm for z-position. For larger tolerances a bottom plate with higher thickness is to be preferred.

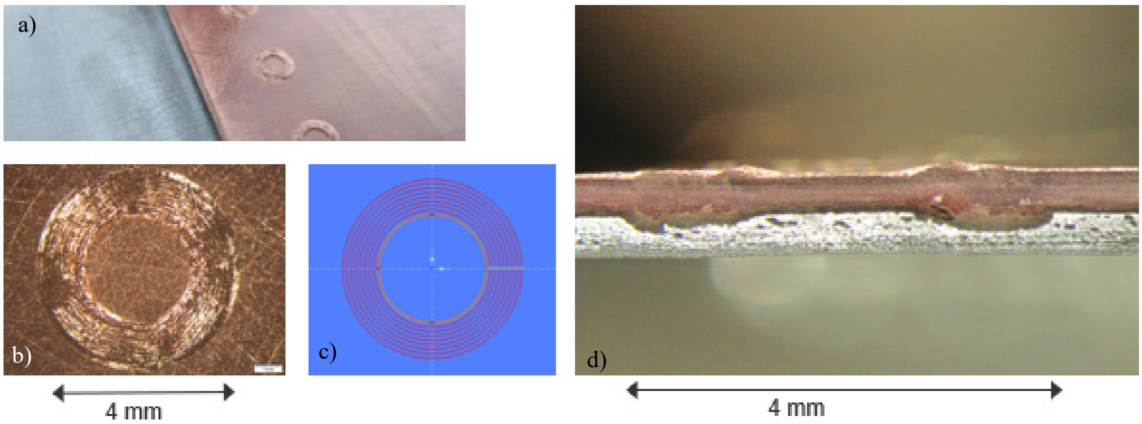

Fig. 3. Hatch welding of Cu on Al a) b) overview and detail of welding from top side c) hatch geometry d) cross section through ring center

As shown from the high-resolution optical images of the cross-section in fig. 4.a), the hatching strategy created an intertwining of pure Cu and Al with a minimal intermetallic phase zone, which was estimated to be < 20 µm as seen in the SEM image fig. 4.c).

The melting temperature of Cu is much higher compared to Al. Therefore, Al overheats, if the isotherm for melting temperature has to cross through Cu to reach Al. A strategy to minimize this effect is to compress the isotherms through high speeds and a small keyhole. The melt pool for hatch welding is as small as possible and therefore quite different to the larger one used for wobble welding. In addition to the isotherm for melting temperature only touching the interface of Cu and Al, the high cooling rate leads to minimization of intermetallic phases and also leaves the Al less time to move to the top which usually happens because Al is lighter than Cu.

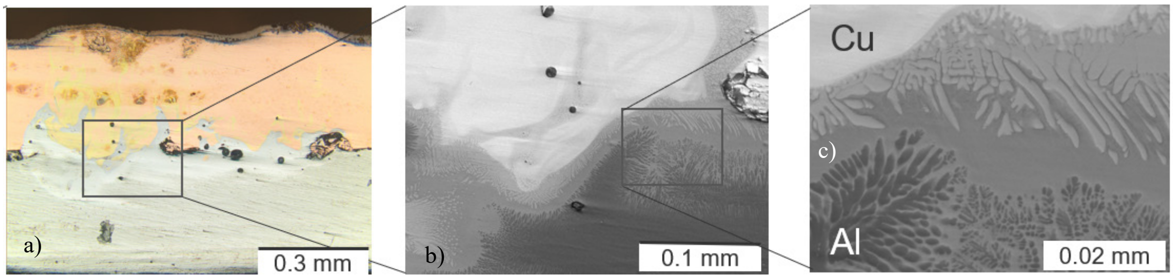

Fig. 4. Hatch welding of Cu on Al, cross section, a) microscopic image b) c) SEM image

Mechanical stress tests of joined Cu-Al samples reached tensile strength > 200N and cross tension strength of approximately 90 N per one ring weld. Evaluation of the electrical properties showed that the conductance of the joint connection using hatch welding was always significantly higher compared to the one achieved with conventional bolted connections.

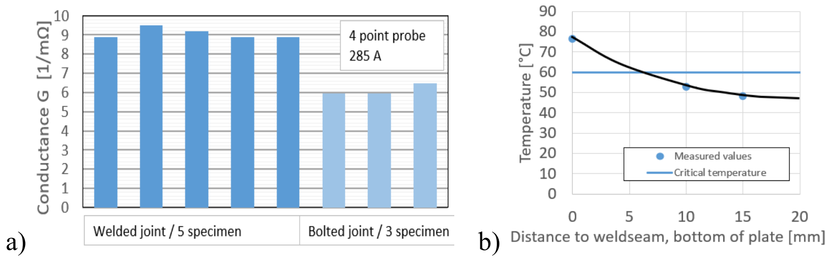

Fig. 5. a) Electrical test of the Cu-Al connection. Comparison of the conductance between joints realized with hatch welding (left) and bolted connections (right), b) Temperature measurements during laser hatching process as function of the distance from the center of the ring.

4. Conclusion

Based on two overlap combinations of Cu and Al we demonstrated different weld strategies for creating connections between materials with dissimilar metallurgical properties, with excellent mechanical and electrical properties. Whereas Al on Cu has always been possible, Cu on Al never had much strength before. The new solution of hatch welding, through isotherm compression and rapid cooling, leads to a favorable mixing of the two materials. High strength, low electrical resistance and cold weld surrounding mark this solution as a versatile tool for battery production.

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