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Remote laser beam welding of copper to aluminum using a frequency-doubled disk laser

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Abstract

When joining copper and aluminum, intermetallic compounds with complex properties can form and negatively affect the mechanical and electrical properties of the weld seam. Laser beam sources with emission in the visible wavelength range enable welding of copper with high process efficiency since its absorptivity is significantly higher there than for the near-infrared wavelength range. In this study, copper was welded to aluminum in an overlap configuration, using a continuous wave laser beam source emitting at 515 nm. Preliminary experiments were carried out to identify a suitable process window for further experiments. Subsequently, the electrical resistance and the tensile joint strength in dependence of the feed rate were determined. Through metallographic cross-sections, the weld seam and the formation of intermetallic compounds were investigated. The results show that dissimilar joints with good physical properties can be obtained using green laser radiation, enabling new possibilities for joining copper and aluminum.

Keywords: green laser radiation; copper; aluminum; dissimilar metals; welding

1. Introduction

Copper (Cu) and aluminum (Al) have a high electrical conductivity and are important materials for various applications in the field of electromobility. The combination of both metals in the form of dissimilar joints is relevant for lithium-ion battery modules. Copper busbars, for example, are welded to aluminum terminals of prismatic battery cells. Due to the low solubility of copper and aluminum, intermetallic compounds (IMC) with complex properties form during solidification (Murray, 1985). The resulting weld seam can be brittle and thus producing a sound joint is a challenging task. Furthermore, the electrical resistance of a joint increases linearly

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with the thickness of the intermetallic compounds (Braunovic et al., 1994). In order to obtain good mechanical and electrical properties for a joint, the formation of IMCs should be kept to a minimum. Table 1 lists the physical properties of the five stable intermetallic compounds in the Al-Cu-system at room temperature (Braunovic et al., 2007).

Table 1. Physical properties of the intermetallic compounds in the aluminum-copper-system at room temperature

symbol	Al in wt %	Cu in wt %	chemical formula	electrical conductivity in µΩ cm	hardness in HV (0.4 N)
θ	45	55	Al_2Cu	8	413
η_2	30	70	AlCu	11.4	648
ζ_2	25	75	Al_3Cu_4	12.2	624
δ	22	78	Al_2Cu_3	13.4	180
γ_1	20	80	Al_4Cu_9	14.2	35

For joining copper and aluminum, processes such as ultrasonic welding, brazing, and laser beam welding (LBW) can be used. The latter is a contactless welding process that does not require any filler material and provides high flexibility and productivity.

Plapper et al., 2016 conducted experiments using pulsed laser radiation for welding aluminum on copper and vice versa. The mechanical strengths and electrical resistances of the weld seams were investigated in dependence of the pulse duration. By additionally applying spatial power modulation, Mathivanan et al., 2019 were able to reduce the intermixing of Al and Cu. Microscopic analysis of longitudinal cross-sections revealed that the number of pores in the weld seam increased proportionally with the degree of intermixing of Al and Cu. Through analysis employing energy-dispersive X-ray spectroscopy and synchrotron X-ray microdiffraction, the fatigue cracks could be attributed to the copper-rich intermetallic compounds. (Zuo et al., 2014; Schmalen et al., 2018).

Fetzer et al., 2016 applied continuous wave (cw) laser radiation, superimposing the linear movement with a sinusoidal oscillation of the laser beam, to weld aluminum on copper. By adjusting the amplitude and frequency of the beam oscillation, the thickness of the IMCs in the weld seam was reduced. Hollatz et al., 2020 used the same approach in combination with a single-mode laser beam source with high brilliance, which improved the weld seam quality significantly compared to multi-mode radiation. The study showed a high-quality welding process for aluminum to copper with good reproducibility based on tensile shear tests, determining the maximum tensile joint strength. A reproducible process for welding copper on aluminum, however, could not be established with near-infrared radiation (NIR).

Copper has a higher absorptivity for radiation in the visible wavelength range than for NIR. When using a beam source emitting at a wavelength of 515 nm, significantly less laser power is necessary to establish a deep penetration welding process (Engler et al., 2011). In their studies, Haubold et al., 2018 observed that the vapor plume during the deep penetration welding process partially absorbed the green laser radiation. A suction was positioned near the process zone to remove the vapor plume from the laser beam path. Thus, more energy was coupled into the workpiece, subsequently increasing the weld depth. Kick et al., 2020 welded copper on nickel-plated steel with green laser radiation. Good mechanical and electrical properties for the joints were obtained and the process had a high reproducibility. Thus, the question arises, whether using laser radiation in the visible wavelength range offers new possibilities for other material combinations. In this paper, experiments were conducted to investigate the potential of laser beam welding of copper to aluminum with a frequency-doubled disk laser.

2. Experimental set-up

The set-up consisted of a laser beam source of the type *TRUMPF TruDisk 1020* with a wavelength of 515 nm, a fiber core diameter of 50 µm and a maximum output power of 1000 W. A *TRUMPF PFO 20-2* with an image ratio of 1:2.93, resulting in a focus diameter of approximately 147 µm, was used as scanning optics. The weld seam length on all samples was 15 mm. Figure 1a shows the experimental set-up including the crossjet, the suction, and the clamping system. All specimens were covered with a protective film preventing oxidation of the surface, which was removed before the welding process. The laser beam was guided by the scanning optics while the clamping system with the specimens remained in a fixed position.

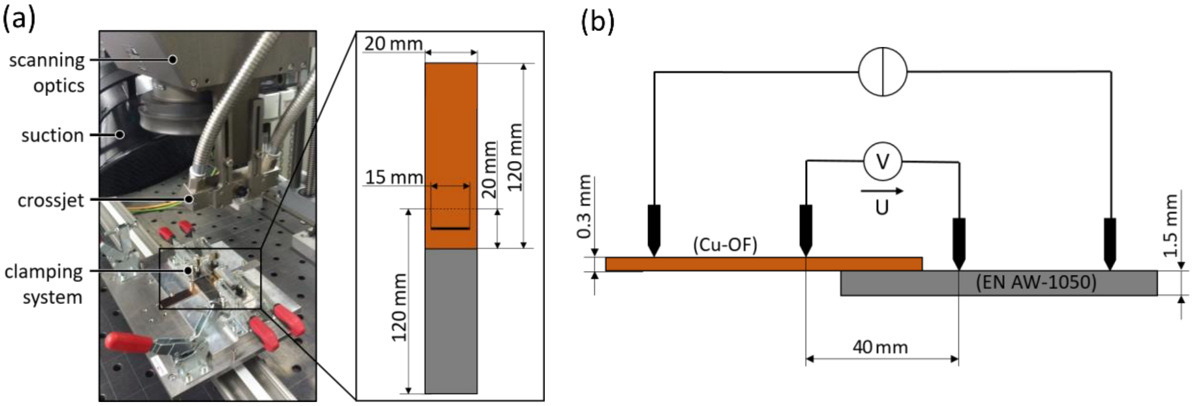

Fig. 1. (a) The laser beam welding set-up and arrangement of the specimens and (b) the set-up for the electrical resistance measurement

Figure 1b shows the set-up for the determination of the electrical resistance based on the four-point probe method. An *R&S HMP4040* as current source in combination with a voltmeter of the type *Fluke 8846A* was used for this study. All measurements were conducted with a current of 10 A. Subsequently, the maximum tensile joint strength was determined based on ISO 14273:2016. A selection of the physical properties of the specimen materials is listed in table 2.

Table 2. Physical properties of the specimen materials

description	material	melting temperature in °C	thermal conductivity in W/(m K)	electrical conductivity in µΩ cm
Al	EN AW-1050	660	237	2.9
Cu	Cu-OF	1084	391	8

3. Preliminary experiments

Preliminary experiments were carried out to identify a suitable process window. A sample was defined as outside the desired parameter range if there was no connection between the specimens or the aluminum sheet was fully penetrated. The process boundaries were experimentally determined for four different laser power values and are indicated by the points in Figure 2a.

Here, the influence of the high absorptivity of copper for green laser radiation was already noticeable, since a joint was established with a laser power of 600 W and a reasonably high traversing speed of 35 mm/s. Interestingly, at a feed rate of 360 mm/s, a bond between the specimens was achieved without any penetration of the aluminum. As indicated by the yellow line in figure 2b, the copper was only partially melted, essentially resulting in a bead on plate weld.

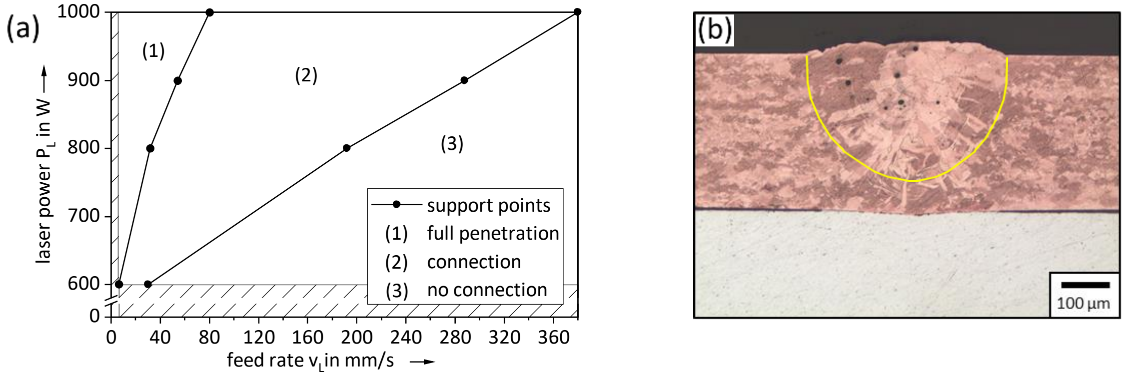

Fig. 2. (a) Investigated parameter space and (b) metallographic cross-section of a weld seam for P_L = 1000 W and v_L = 360 mm/s

The clamping system used in this investigation provided a good thermal contact between the specimens. Although the laser beam did not fully penetrate the upper joining partner, it can be assumed that the melting temperature of the aluminum was reached at the interface of the specimens due to the high thermal conductivity of pure copper. A thin melt film developed, creating a bond after solidification.

For the following experiments, the laser power was kept constant at 1000 W to investigate the mechanical and electrical properties of the joints as a function of the feed rate. The parameter combinations were reduced, after the initial experiments revealed that for feed rates below 180 mm/s the weld seams were brittle and sensitive to fatigue cracks during handling. All parameter combinations were executed four times, resulting in a total of 40 samples for the following measurements.

4. Investigation of the electrical resistance and the tensile joint strength

Each sample was measured three times and the acquired values were averaged. The electrical resistance as a function of the feed rate is illustrated in figure 3a. For a feed rate of 260 mm/s the lowest electrical resistance was obtained.

The corresponding metallographic cross-section in figure 3b shows a cone-shaped weld seam and a formation of IMCs predominantly in the copper specimen. A further reduction of the feed rate had a negative effect on the electrical conductivity. Due to the high energy input below a value of 260 mm/s, the weld depth increased and more of the aluminum was melted, resulting in an increased share of IMCs in the weld seam. The overall highest electrical resistance, as well as the highest variation, were found for feed rates above 320 mm/s. This may be caused by the low bond width between the specimens.

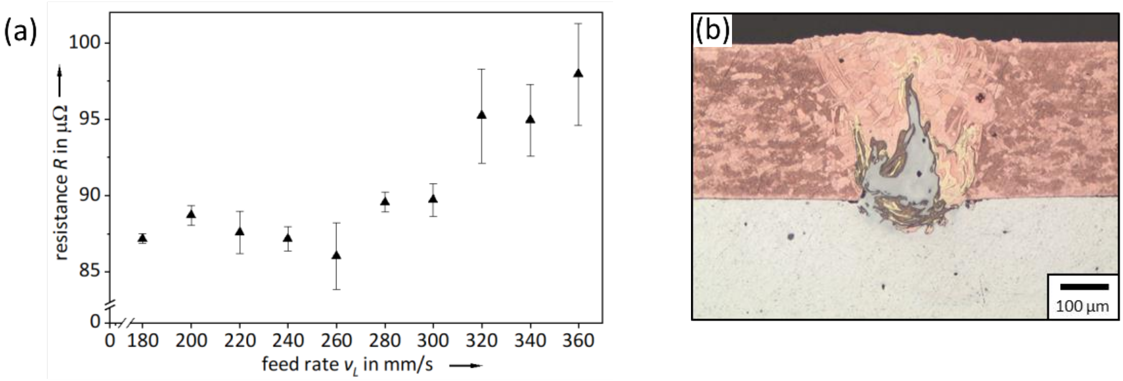

Fig. 3. (a) Electrical resistance over the feed rate and (b) metallographic cross-section of a weld seam for P_L = 1000 W and v_L = 260 mm/s

The influence of feed rate on the mechanical strength was found to be more significant than on the electrical resistance. The highest mechanical strength was identified at a feed rate of 240 mm/s, with the lowest variation across all parameter combinations.

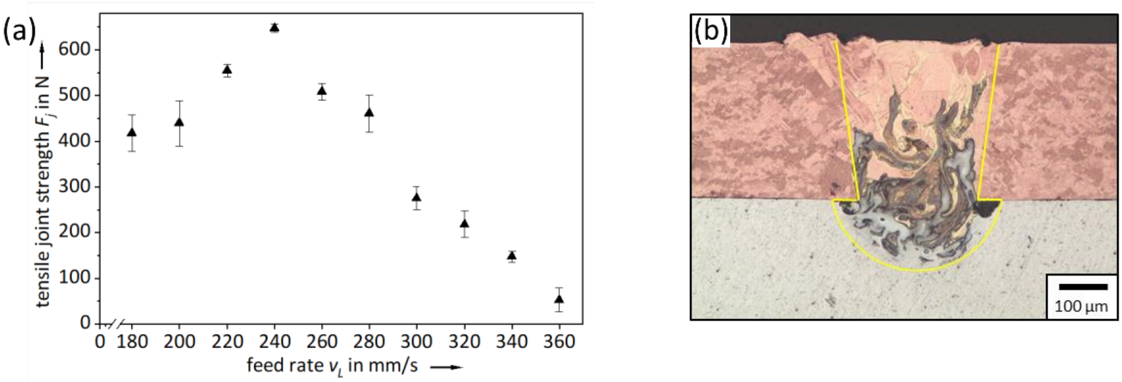

Fig. 4. (a) Tensile joint strength over the feed rate and (b) metallographic cross-section of a weld seam for P_L = 1000 W and v_L = 240 mm/s

Furthermore, as indicated by the yellow line in figure 4b, an increase in weld seam width was observed for a feed rate of 240 mm/s. The high energy input at this feed rate in combination with the low melting temperature of the aluminum resulted in more molten material compared to the copper. Similar observations were reported by Hollatz et al., 2020 in their studies. There, the effect occurred for all parameter combinations, since a high laser power was required by default to establish a deep penetration welding process due to the low absorptivity of copper for NIR.

The observed pore formation in the metallographic cross-section in figure 4b is a characteristic phenomenon for laser beam welding of aluminum. According to Schinzel et al., 1998, it is caused by instabilities of the keyhole or as a result of the sudden reduction in hydrogen solubility of the aluminum at the melting temperature. Due to the short process time and the narrow weld seam width in the copper specimen, the gas has no time to escape and is trapped during solidification.

5. Conclusion and summary

For this paper, the potential for laser beam welding of copper to aluminum using green laser radiation was investigated. Through preliminary experiments, a process window was identified for producing joints in overlap configuration without full penetration of the lower specimen. The increased absorptivity of copper for green laser radiation enabled a connection with a laser power as low as 600 W at a reasonable feed rate. Subsequently, the electrical resistance and the tensile joint strength were determined in dependence of the feed rate for a laser power of 1000 W. The measurements showed good results, though the lowest electrical resistance and the highest mechanical strength could not be achieved with the same parameter set. The findings show that by using green laser radiation, copper and aluminum can be joined successfully.

Further studies should analyze the IMCs in detail by means of synchrotron X-ray microdiffraction to allow for a comparison to welding processes using near-infrared laser radiation. Furthermore, additional experiments should be carried out to investigate the potential of temporal and spatial power modulation in order to improve the weld seam quality and keep the formation of the intermetallic compounds to a minimum.

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