Lasers in Manufacturing Conference 2021

Process control of aluminum-copper mixed joints during laser beam welding in vacuum

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Abstract

The creation of aluminum-copper mixed joints is difficult to produce in all welding processes. This is due to the unavoidable formation of intermetallic phases (IMP), which reduce the mechanical technological properties of the weld, and to the different melting points of pure aluminum and copper. Laser beam welding in vacuum with a single-mode fiber laser ensures precise temporal and local energy input, allows a controlled degree of melting copper, and homogeneously mixes both materials. This paper reports the recorded radiation characteristic of the mixed joint in vacuum to determine the degree of copper and consequently the IMP. Therefore, we detected the characteristic copper wavelength 521.8 nm and correlated the intensity to the copper content and IMP in the weld. The copper content and the IMP in the weld seam do not correlate to the resistance that we measured with the four-wire method.

Keywords: laser beam welding; mixed joint; aluminum; copper; LaVa

1. Introduction

Automotive industry is one of the main forces in developing laser welding processes since the high investment is subsidized by the quantity of parts as shown by Li, 2018. Constantly growing interest in electric cars, plug-in hybrids, and fuel cells promotes the Bundesamt für Wirtschaft und Ausfuhrkontrolle, 2020 bonus program, but also it requires a greater need of innovative solutions in production. These include the electrical components and thus aluminum copper mixed joints as shown by Fortunato, Ascari, 2019 and Brockmann et al., 2018. Lee et al., 2014, Schmidt et al., 2012 and Fetzer et al., 2015 reveal different approaches to produce the aluminum-copper mixed joint (ACM) while all joints are showing hard

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intermetallic phases (IMP). These IMPs reduce the mechanical properties and manifest a higher electric resistance. As a process control, Schmalen, Plapper, 2018 and Seibold et al., 2019 use the approach with spectroscopy measurement. Another opportunity from Schmalen, Plapper, 2017 is to quantify the electrical resistance of each weld seam and correspond it to the quality of the connection. A further, more promising technology in welding aluminum to copper is laser welding in vacuum with a single mode fiber laser as shown in Reisgen et al., 2018. The IMP is reduced to a minimum of 3 µm and no measurable difference in the electric resistance is detectable. Therefore, a quality control process for the ACM produced by laser beam welding in vacuum is required that is usable in industry. Within the scope of this work, we determine the quality of the currently used 4-point resistance measurement and record the radiation of the weld pool in vacuum in order to compare it with the size of the IMP in the weld seam.

2. Experimental Setup

2.1. Material

This study uses pure aluminum and copper with a sheet thickness of 2 mm, welded together as a butt joint. Table 1 lists the chemical analysis of the used material. Each sample has a size of 100x150x2 mm. To make sure the surface quality is the same, we treated each sample with abrasive fabric (fabric pattern 220) and removed impurities with acetone.

Table 1. Chemical composition from the optical emission spectrometry

Chemical element	Al	Cu	Si	Fe
Cu	0.0051	99.9	0.0002	0.0224
Al	99.5	0.0086	0.105	0.343

After welding two samples together, three rectangular pieces are for the scanning electron microscope and the energy dispersive X-ray spectroscopy of the weld. Another four bone-shaped pieces (see **Fehler! Verweisquelle konnte nicht gefunden werden.**) are for tensile tests and the resistance measurement.

2.2. Welding Procedure

The used laser beam source for welding is the IPG YLS-2000-SM fiber laser with a maximal output of 2000 W. This single mode laser emits a wavelength of 1075 nm and reaches a beam parameter product of 0.39 mm·mrad. The connected fiber with the used IPG D50 2D scanner optic generates a spot size of 70 µm that corresponds to a magnification ratio of 2:1. An additional coaxially aligned camera enables exact positioning of the laser beam. The parameters beam offset, line energy, intensity, pressure, oscillation, and type of joint vary to achieve different welding qualities and to recognize the impact on the weld.

2.3. Resistance Measurement

As in Gintrowski et al., 2019 and Reisgen et al., 2019, we use the four-point measurement method for quantifying the weld seam quality. Therefore a measurement current I_M of 180 A passes through the specimen (see **Fehler! Verweisquelle konnte nicht gefunden werden.**) and a voltmeter measures the voltage drop between the four points (M1, M2, M3, M4), each 40 mm apart. The voltage difference (U_{Al}, U_{ALCu}, U_{Cu}) divided by the measuring current results into the electrical resistance. The cross section between the measurement points M1-M2 and M3-M4 shifts from 48 mm² to 24 mm², which increases the electrical resistance of the base material aluminum and copper. In order to have a direct comparison of the electrical resistances, we took 20

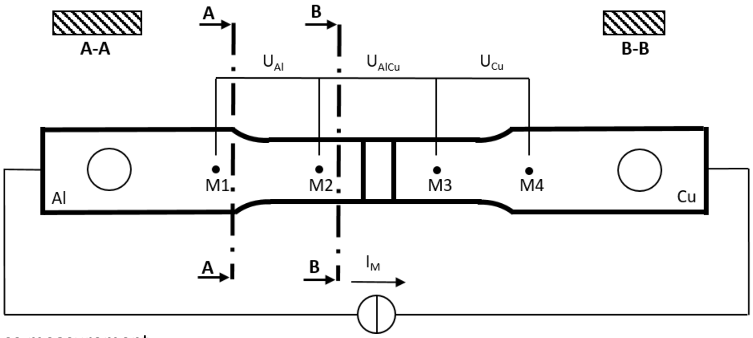

Fig. 1: Four-point resistance measurement

repeated measurements from the base material with identical cross-section to the weld, see Fig1 B-B, and calculated the average value. These reference measurements for aluminum and copper indicate a resistance of 51.495 µΩ and 36.381 µΩ, respectively, and serve for the assessment. For the assessment, the contact value K_U serves as the comparative value which establishes the ratio of the double resistance of the mixed joint to the sum of the resistances of the base materials as shown in Jarwitz et al., 2018, Schmalen, Plapper, 2017, Bergmann et al., 2013 and Eslami et al., 2018. The optimum is a value of $K_U = 1$ whereas higher values mean higher resistance.

2.4. Spectroscopy

Beside the four-point resistance measurement for quantifying the quality of the mixed joint, spectroscopy measurement is possible as a real-time monitoring process. Here, the characteristic wavelength of aluminum (394 nm, 396 nm, 670 nm) and copper (510 nm, 515 nm, 522 nm 578 nm) are detected as shown in Schmalen, Plapper, 2018 and Seibold et al., 2019. The used Ocean HDX-XR spectroscopy camera records the spectrum from 191 nm to 1126 nm at time intervals of 10 ms. The range from 900 nm to 1126 nm is not detected in the measurement because of the laser safety glass, which is the interface between atmospheric and vacuum that filters out this wavelength range. Fig. 2 (a) shows the position of the spectroscopy camera and schematic structure in this experiment. We tilt the spectroscopy camera by -18° to the surface normal and the laser optic

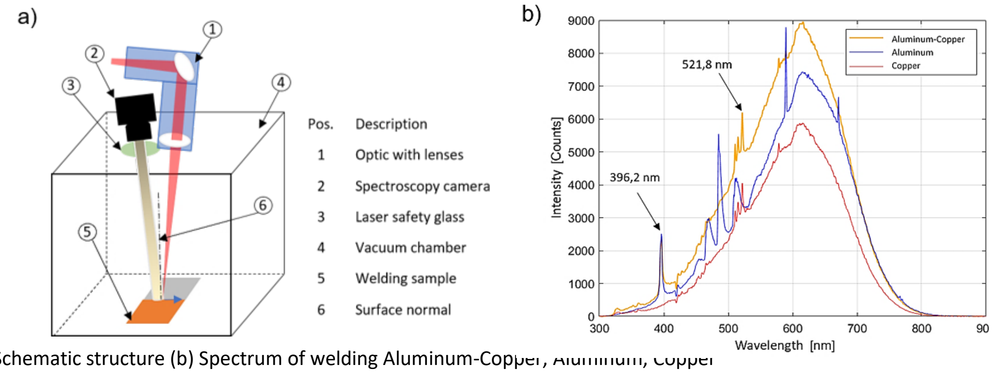

Fig. 2. (a) Schematic structure (b) Spectrum of welding Aluminum-Copper, Aluminum, Copper

by +5°. The angle adjustment for the laser optics is necessary in order to prevent damaging caused by laser reflection. Fig. 2 (b) presents a snapshot of the spectrum by welding pure copper, pure aluminum, and a mixed joint of aluminum-copper. This serves as a proof that the mentioned characteristic wavelength of aluminum and copper are detectable with laser welding in vacuum as it is in Schmalen, Plapper, 2018. For analysis, we used the wavelengths 396.2 nm (aluminum) and 521.8 nm (copper).

3. Results

3.1. Electrical Resistance

The measured electrical resistance and the following calculated contact value K_U stay the same for all variations of the five different parameters as shown in Fig. 3 (a), while the quality of the weld seam is highly different. Fig. 3 (b) presents a solid weld between aluminum and copper at an ambient pressure of 100 mbar. Identical parameters - only at an ambient pressure of 200 mbar - indicate huge pores while the contact values stay the same within the measurement accuracy. The measured resistance of the weld is between 43.75 – 44.09 µΩ, which is within the measurement inaccuracy. This shows a 20-fold repeated resistivity measurement of the same weld sample that yields to a standard deviation of 0.327 µΩ. Hence the fluctuation is too high to evaluate the 2 - 10 µm narrow IMP. Assuming, the natural oxide layer of the base materials has a major influence, which increases the contact resistance between the measuring tip and the measuring point and increases the fluctuation due to inconsistent surface. A parallel connection of two measuring tips next to each other can reduce the inconsistency since it halves the contact resistance.

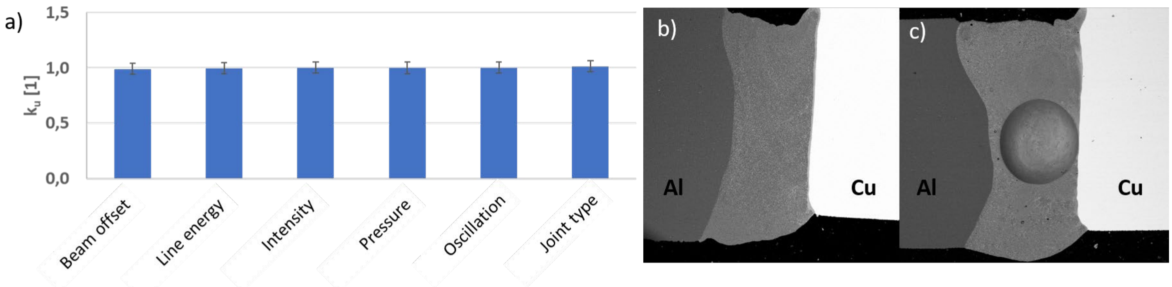

Fig. 3. (a) Contact value of all varied parameters (b) good weld seam quality (c) poor weld seam with pores

The sequential resistance measurement used by Schmalen, Plapper, 2017 measures the local resistance of the welded joint through two opposing measuring probes. Critically, however, the contact resistance can also significantly change due to the uneven weld bead and root as shown in Fig. 4. In addition, current flows along lowest resistance, which means when measuring the butt joint, current can also flow along the base material

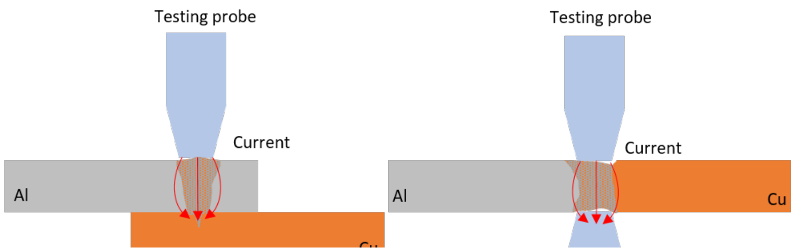

Fig. 4. Local resistance measurement according to (Schmalen, Plapper, 2017)

and through the weld. Hence the so far used four-point resistance measurement method and the sequential resistance measurement are not suitable for measuring the higher resistance caused by IMP in laser beam welded parts. This method is more suitable for friction stir welding or other welding processes that produce thicker weld joints.

3.2. Spectroscopy

The 0.3 mm beam offset on the aluminum side shows in the SEM exposure an approximately homogenous mixed joint with an overall copper content of 5.6 – 7.7 at.% as shown in Fig. 3 (b). Oversaturated aluminum-solid-solution (M) with a copper content of 6.37 at.% has the main portion in the weld seam followed by eutectic mixture (E) and IMP (I) with a copper content of 18.96 at.% and 37.23 at.%, respectively, as seen in Fig. 5 (a). The SEM exposure of 0.2 mm beam offset in Fig. 5 (b) measures a copper content of 24.94 at.% and registers an increase in pores and cracks. In this weld seam, IMP in a eutectic mixture has the main portion. On the opposite, the 0.4 mm beam offset (c) presents an identical structure to the beam offset of 0.3 mm. They distinguish in a slightly finer precipitates of the oversaturated aluminum solid solution whereby the copper content is roughly the same at 5.29 at.%.

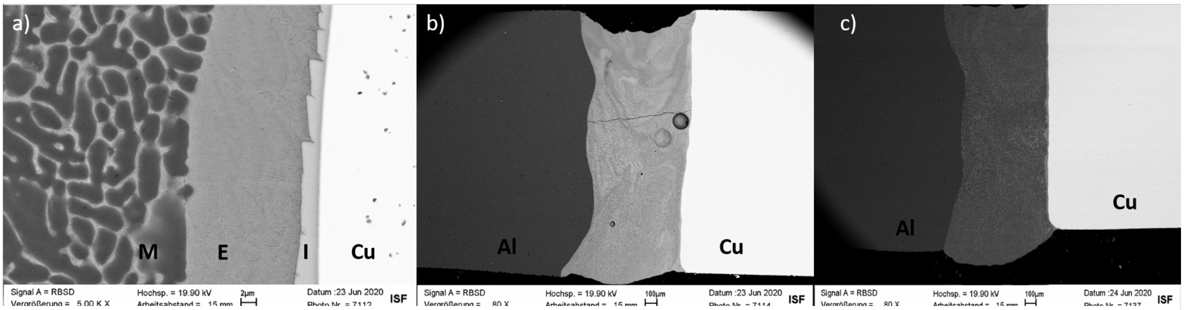

Fig. 5. SEM exposure (a) standard parameter with beam offset 0,3 mm (b) beam offset 0,2 mm (c) beam offset 0,4 mm

The spectroscopy measurements correlate to the copper content and beam offset as shown in Fig. 6. The intensity rises while the copper content in the weld seam increases by a beam offset of 0.2 mm. Further distance to the copper sheet results in a decrease in copper content and intensity of the characteristic copper wavelength of 521.8 nm. We measured the same correlation by varying the line energy.

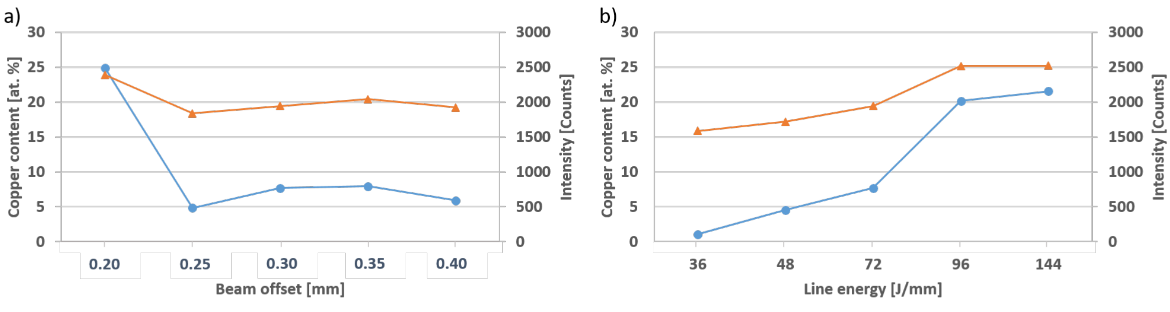

Fig. 6. Correlation between copper content and wavelength intensity by (a) beam offset and (b) line energy variation

The time-base view on the spectroscopy measurement reinforces the correlation between intensity of the characteristic wavelengths and the copper content as shown in Fig. 7. In the beginning, strong fluctuations in measurement represent the instable keyhole before it stabilizes to a roughly constant value of around 2600-3000 counts. At the end of the weld seam, strong thermal distortion decreases the beam offset of the laser closer to the copper side while increasing the intensity of the copper wavelength. Conversely, the aluminum wavelength 396.2 nm decreases.

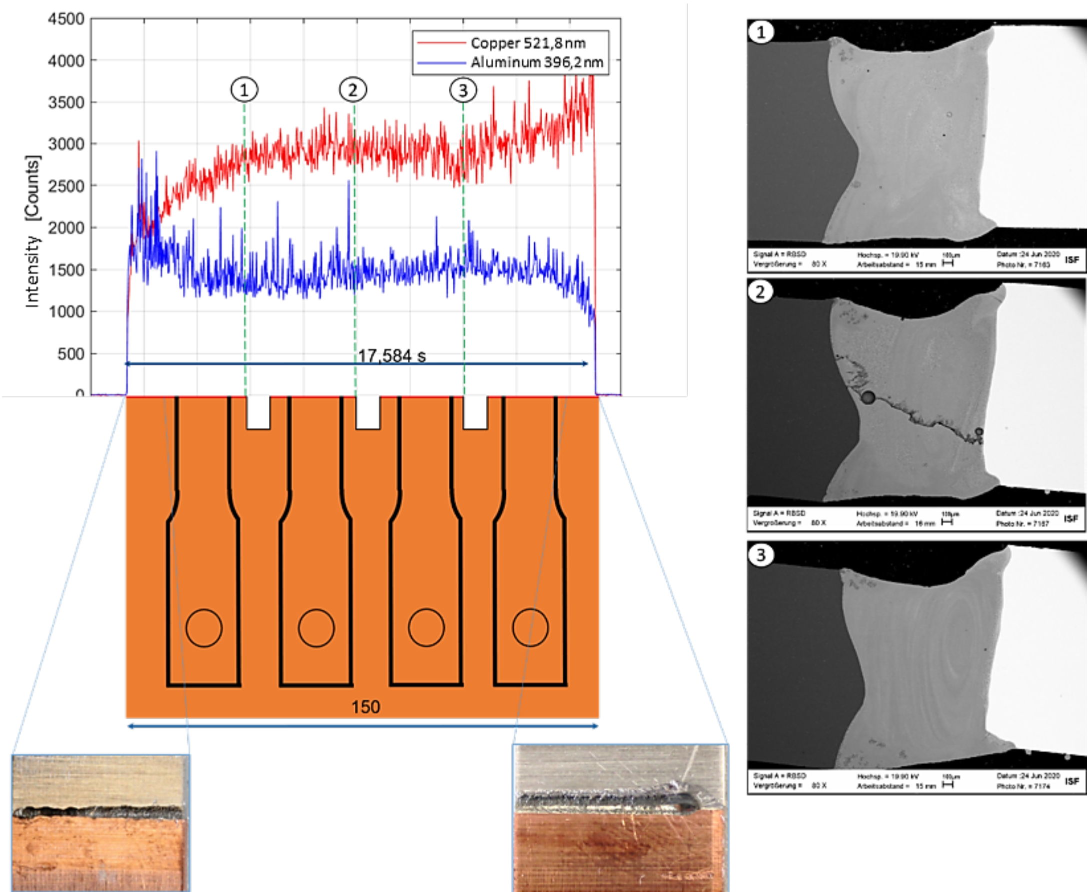

Fig. 7. Time based spectroscopy measurement

The superposition of the spectroscopy measurement shows that the beam offset drifts to the copper side. This change is due to the high line energy input of 144 J/mm, which causes an increasing melt pool and a higher distortion. While the beam offset of 0.3 mm stays the same at the beginning, a clear offset onto the copper sheet can be seen at the end, which is reflected in the intensity of the copper wavelength. The EDX analyses at the positions 1, 2 and 3 show a copper content of 20.87 at.%, 21.55 at%, and 18.94 at.%, respectively. The copper wavelength of 521.8 nm measures an intensity about 2700 counts at position 1 and increases to roughly 3000 counts (position 2), before it drops to 2600 counts at position 3. The analysis of the aluminum wavelength 396.2 nm at position 2 indicates a short preceding peak that could correlate to a blowout. This might be the origin of the crack, which is visible in the SEM exposure. A verification and confirmation of the assumption by X-ray is not possible, since the widely separated density values of aluminum and copper lead to either overexposure or underexposure of the X-ray image. Furthermore, it can be assumed that the copper content of the entire weld of approx. 20 at.% is the limit value for crack formation. The copper content varies between 14.4 - 20.2 at.% at a lower line energy of 96 J/mm, whereby the first crack formations can be seen. Identical results presents the beam offset of 0.2 mm, which measures a copper content of 24.94 at.%. This result rejects the presumed hypothesis (we had at the beginning of the research) that the ACM behaves like an aluminum alloy 2000, which has a tendency to hot cracks at around 0-10 at.%.

4. Conclusion

The so far used four-point measurement method are not suitable for a quality check of an aluminum-copper mixed joint welded by laser welding in vacuum. This is due to the very thin weld seam that contains reduced IMP. This leads to no significant change in electrical resistance between a good and a poor weld, whereas the contact value stays at $K_U = 1$. The measured resistances present a variation between 43.75 – 44.09 µΩ due the natural oxide layer and an uneven surface of the base material. Hence, pores, cracks and other defects are subject to the measurement standard deviation of 0.327 µΩ. The more promising measurement method for monitoring and qualifying ACM is spectroscopy measurement during the welding process. We demonstrated that spectroscopy measurement in the LaVa process is possible despite lower plasma luminosity in vacuum. The characteristic wavelengths of aluminum 396.2 nm and copper 521.8 nm are detectable in the spectrum of mixed joint welding. The intensity of those wavelengths correlate with the copper content by variating beam offset and line energy. We also detected cracks at a measured copper content above 20 at.%. An extension of the spectroscopy measurement with a photodiode and an edge filter of the corresponding wavelength obtains higher sampling rates. This can provide detailed information about the copper content along the weld seam and verify its relationship to the emitted intensity of the characteristic copper wavelength. If the emitted intensity of the copper wavelength correlates to the copper content and the IMP, real-time monitoring of the welding process is possible and the separate electrical resistance measurement is no longer required, Consequently, this non-destructive weld seam check recognizes irregularities while laser welding in vacuum and sorts out the faulty weld seams.

Acknowledgements

The RWTH Aachen University – Welding and Joining Institute (ISF) thanks the German Research Foundation (DFG – Deutsche Forschungsgemeinschaft) for their support and funding. The research work and results presented above were made in the context of the DFG-Project “Einfluss von Wärmezyklus und Aufmischungsgrad beim Elektronenstrahlschweißen auf Eigenschaften und Langzeitverhalten von Aluminium-Kupfer-Mischverbindungen in stromdurchflossenen Bauteilen”, DFG RE 2755/48-1.

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