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Investigation in welding Aluminum-copper joints by using modern welding strategies with a green laser beam source

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Abstract

Automobile electrical system has continued to develop in recent years. Copper enables the use of high electrical currents due to its high electric conductivity but is increasingly being replaced by aluminum to reduce weight and costs. Aspects such as contact erosion prevent the complete replacement of copper, so that mixed joints are gaining importance. However, the low solubility between aluminum and copper leads to the formation of disadvantageous intermetallic compounds. This paper describes an indirect joining process between copper and aluminum in which copper is heated by a laser beam while aluminum gets molten at the interface due to heat conduction. The aluminum melt wets the solid copper surface while the formation of intermetallic compounds is significantly limited by avoiding a common melt pool. Different joining strategies were studied by laser beam sources enabling a sufficient energy input and a stable processing of copper, i.e., green high-power lasers and concentric IR high power laser.

Keywords: Aluminum-copper joints; laser welding; temperature measurement

1. Introduction

Electro-mobility is a steady growing market, which seems to grow faster and faster in recent years. In 2021, 44% of all newly registered vehicles in Germany should be built with an alternative drive system such as plug-in hybrids or electric drive [1]. As better concepts continue to emerge, new challenges are emerging. Copper

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is an essential material, especially for energy transport. Because of its high electrical conductivity and good mechanical properties, copper is indispensable in this field. The disadvantage is its high density. In order to save weight and costs, copper is replaced by aluminum. Due to contact corrosion, among other things, a complete replacement of the copper material is almost impossible. Therefore, the formation of aluminum-copper mixed compounds cannot be avoided. This in turn leads to further challenges. The low mutual solubility of the two materials leads to the formation of intermetallic compounds during solidification in welding processes [2]. These compounds exhibit high electrical resistance and brittle mechanical behavior. The challenge in joining this pair of materials is therefore to eliminate or minimize these intermetallic compounds. This can be accomplished in a number of ways. On the one hand, it is possible to keep the mixing as low as possible by using a closed-loop control system [3]. Another approach to the melt joining process is to strongly mix the melt pool. This results that more material can go into solution. On the other hand, due to the high melt pool dynamics, the intermetallic compounds can form outside the joining zone [4, 5]. A conventional case is to choose a solid-state welding process such as ultrasonic welding. In this process, the melting temperature of the two joining partners is not reached. Nevertheless, a strong joint is formed by high local plastic deformation of the materials. [6]

Another approach is to melt only one joining partner. This can be achieved, if the joining temperature is above the melting temperature of the first joining partner and below the melting temperature of the second joining partner. In this case, it is not possible to form a common melt pool, which has a positive effect on the formation of intermetallic compounds. Without a common melt pool, the atomic lattice structures of the first material remain intact, preventing or at least limiting the formation of intermetallic compounds. Single-sided resistance spot welding is a good method for this. This approach was pursued in this process with the material combinations aluminum steel and plastic metal. [7, 8]

A similar but still newly strategy is presented in this paper. To avoid the formation of intermetallic compounds, only one of the two joining partners is melted. To achieve this, the welding depth must be precisely maintained, which is highly challenging. Achieving a consistent weld depth over time is challenging Copper shows a high tendency to produce weld irregularities during infrared line welding [9]. With modern beam sources, there are several ways to avoid this. In addition to using a beam source that emits in the green wavelength range (λ_{green} = 515 nm), there are a number of IR laser beam sources that have a core-ring power distribution. The freely adjustable power distribution allows the surrounding weld area to be heated or melted in order to influence the temperature gradient and the keyhole diameter so that the welding process is stabilized [10]

The addressed approach is practicable due to the large difference in the liquidus temperatures of the two joining partners. Aluminum, such as the EN AW-1050A used, has a liquidus temperature of $t_{Al,liquid}$ = 660°C, while the copper material used melts at $t_{Cu,liquid}$ = 1083°C. In the experiments, the welding is performed in a lap joint, with the laser beam set on the upper copper side. The keyhole should form close to the interface but avoid not reach it. This is to ensure that the copper material is in the solid phase at the interface while still reaching the melting temperature of aluminum. A temperature between 660°C and 1083°C must be reached at the interface. For the characterization of the weld, it is important to know whether the keyhole reaches the lower joining partner or not. Since the heat conduction between a weld with molten aluminum, a weld without connection, and a weld in the lower joining partner differs significantly, it should be shown that this state can be detected with the temperature measurements. The disadvantage here is that the temperature does not provide any information about the location of the permanent weld during line welding. In addition, to obtain a time-resolved signal, a multichannel spectrometer is used in the experiments with a beam source emitting in the green wavelength range.

In this publication, a new approach, which can be implemented will be described. Further solutions and remarks on rising challenges will be given. Special attention is given to the detection of welding defects.

2. Experimental Setup

In the experiments, mainly the following two beam sources were used. The technical data are listed in the table below. The results for other laser sources are comparable and were presented in detail at the LaserEMobility Workshop 2023 in Milano.

Table 1.

Laser beam source	**TruDisk 3022**	**Coherent HighLight ARM 7500**
System	Brightline weld	Adjustable Ring Mode (ARM)
Wavelength [nm]	515	1070
Max laser power [W]	3000	2000 / 5000
Fiber diameter (core / ring) [µm]	150 / 600	50 / 200
Focus diameter (core / ring) [µm]	285 /1140	106 / 330

The experiments have in common that a welding speed of v_{weld} = 6 m/min was chosen. The core-ring distribution of the beam sources allows a high degree of freedom in the power distribution. The decisive factor for joining the mixed connection is the application of a joining force. In addition to the thermal expansion of both materials, an additional contact pressure is necessary. This counteracts shrinkage during solidification and supports wetting of the molten aluminum on the copper sheet. A specially engineered clamping device was used to achieve this. This is shown schematically in Figure 1 below.

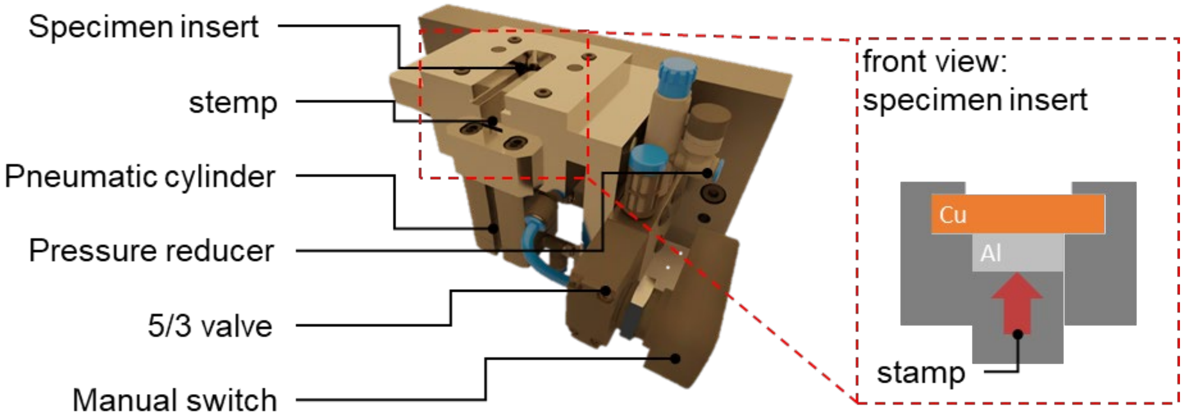

Fig. 1. Computer generated image of the used clamping system

Pure aluminum EN AW-1050A and pure copper Cu-ETP were used in all experiments. The copper samples were 23 x 50 x 2 mm^3 and the aluminum samples were 12 x 50 x 2 mm^3. The copper specimens are placed in the top cutout of the mask to allow access to the laser beam. Line welds with a seam length of 12 mm were made for this study. In contrast to a conventional resistance spot weld, the joining pressure in this fixture is applied via the lower joining partner. The reason for this is that the laser beam must be accessible from the top of the specimen. The use of a stamp under the aluminum specimen ensures that the force is applied over a wide area, which is achieved using a pneumatic cylinder (AND-25-20-A-P-A) from Festo. Due to the maximum permissible pneumatic pressure of 1 MPa, a joining force of up to 490 N can be achieved. This is transferred to a 12 x 12 mm² stamp.

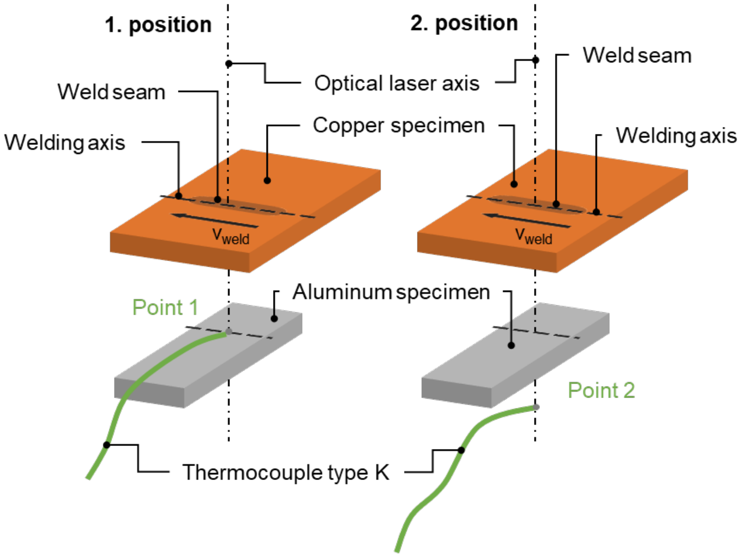

Fig. 2. Simplified arrangement of the experimental setup

Type K thermocouples were used to measure the temperature. With a sampling rate of 5 kHz, a temporally detailed observation is possible. Two different positions were chosen for the thermocouples during welding. The first position is between the two test specimens at the level of the weld seam and thus remains in the weld seam (Point 1). However, from the point of view of quality management, this does not make practical sense, which is the reason, a measurement was also taken at a second position, between the specimen and the stamp (Point 2). The temperature measured at this point is determined by the heat conduction of the aluminum specimen and the heat transfer of the joining zone. The advantage over the first measuring point (Point 1) is that there is better contact between the two joining partners. A disadvantage of this measurement method is the influence of heat conduction. This heat conduction results in a delay in the temperature in the bottom of the specimen with regard to the welding process. For this reason, it is significantly more difficult to conclude from the measured temperatures that local weld defects are present. The following figure (Fig. 2) shows these two selected setups.

3. Results

One of the main goals in the realization of this principle is to achieve the temperature range (660°C – 1080°C). It is necessary to exceed the melting temperature of aluminum while not exceeding the melting temperature of copper. Figure 3 below shows the temperature measured in the center of the joint between the two joining partners. All welds shown were made with the same welding parameters. A core power of P_{core} = 1700 W and a ring power of P_{ring} = 5000 W were applied. The joining force was kept constant at 490 N.

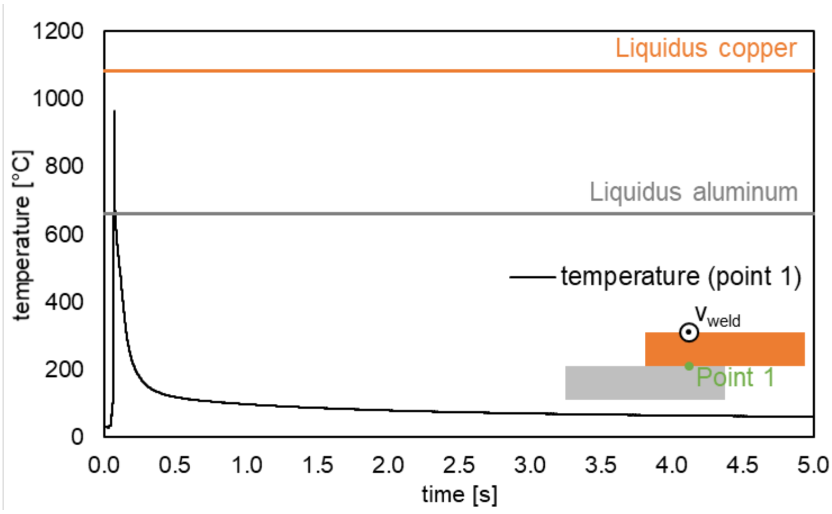

Fig. 3. In situ temperature measurement at measuring point 1 during the laser welding process.

It can be seen that the temperature during welding exceeds the melting temperature of aluminum for 10.5 ms and reach am maximum temperature of T_{max} = 965.73°C. This proves that the desired temperature range is reached to melt the aluminum material. The joining pressure prevents the liquid aluminum from wetting the copper specimen. In order not to negatively affect the wetting by a thermocouple, further temperature measurements were made below the aluminum specimen. The temperatures measured reflect both the heat conduction through the aluminum specimen and the heat conduction at the interface. Since the joining process does not involve a common melt pool, it is necessary that the lower joining partner, in this case aluminum, is melted. The temperature measurements (Fig. 4) show a marked difference.

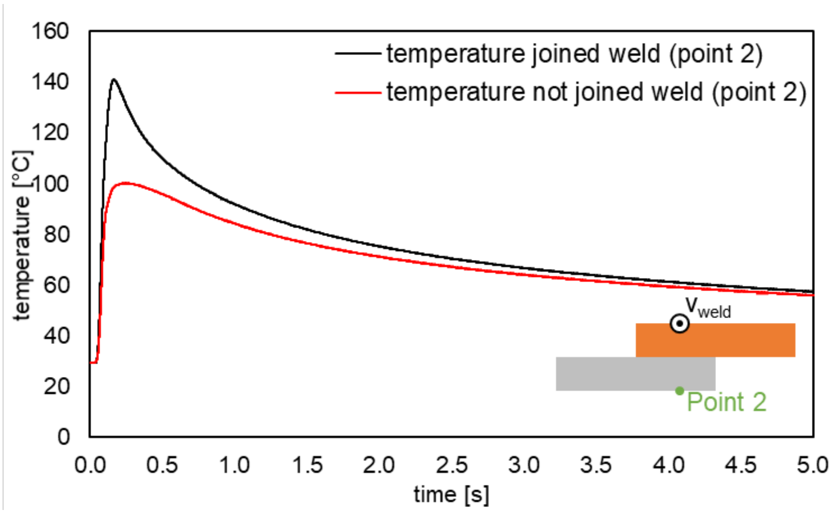

Fig. 4. Temperature measurement at point 2 of a connected and unconnected joined weld.

The figure 4 shows the mean value of temperature measurements for welds that are connected (black) and a weld without connection (red). The weld without connection shows significantly lower temperatures despite the same laser power parameters. This can be explained by the lower heat conduction at the interface when the aluminum material is not melted. Due to welds that were recorded as connected, a maximum temperature of approx. 137°C to approx. 146°C on the aluminum bottom can be detected. This temperature range of 140.5°C ± 4.5°C differs significantly from the maximum temperature of an unconnected weld with only 100°C. This significant deviation of approx. 50 % allows the weld to be quantified via the temperature measurement. For a closer look at the weld, the joint was examined in more detail below.

The interfaces in the following figure 5 show the weak boundary condition of this compound. Similar as before all the following figures correspond to welds with the same laser power parameters. The lower copper side of the interface is shown after separation of both sheets. The solidified molten aluminum adheres to the bottom sides of the copper specimens. Figure 5 a) depicts very well that the amount of molten aluminum was not sufficient to achieve a load-bearing joint. In the Figure 5 b), significantly more aluminum remained on the copper sample. On the separated interface, it can be seen that the weld has partially broken out outside the interface. With a further increase in the welding depth, up to the aluminum material, this punctual coupling leads to “unbutton” in the interface. These points can be seen in Figure c). In general, it can be stated that a mostly cohesive failure from a) to c) can be recognized.

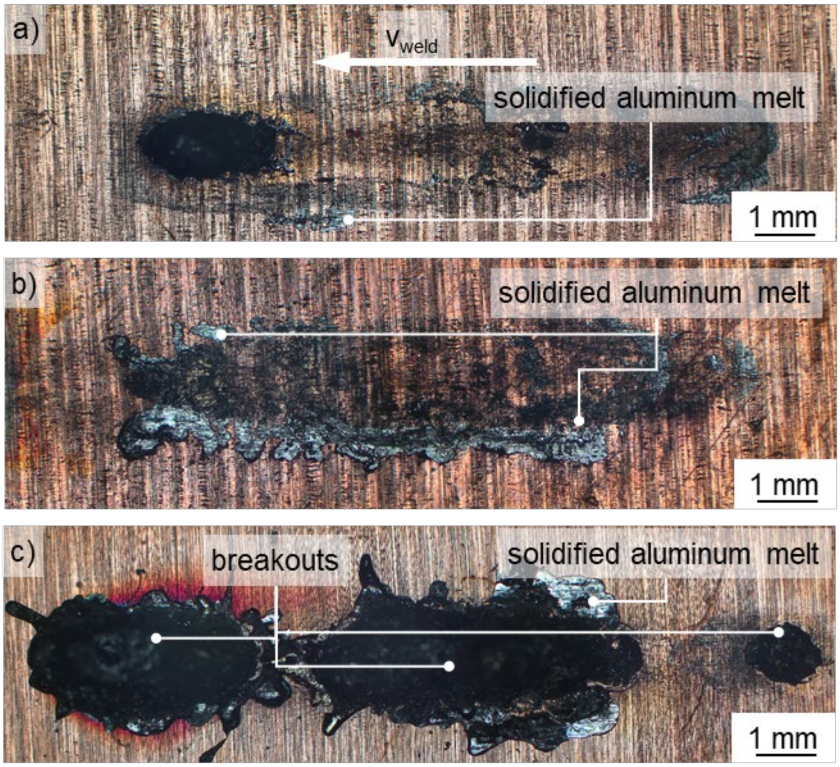

Fig. 5. Images of the copper underside of welds with constant laser parameters. a) no load-bearing welding. b) more molten aluminum. c) Weld seam with multiple breakthroughs of the copper specimen.

Although welding copper with a green laser wavelength results in a quieter molten pool due to the high absorption, the challenges described above also apply here. Due to the significantly higher absorption, the laser power could be reduced. The laser power was set at 3 kW only in the core.

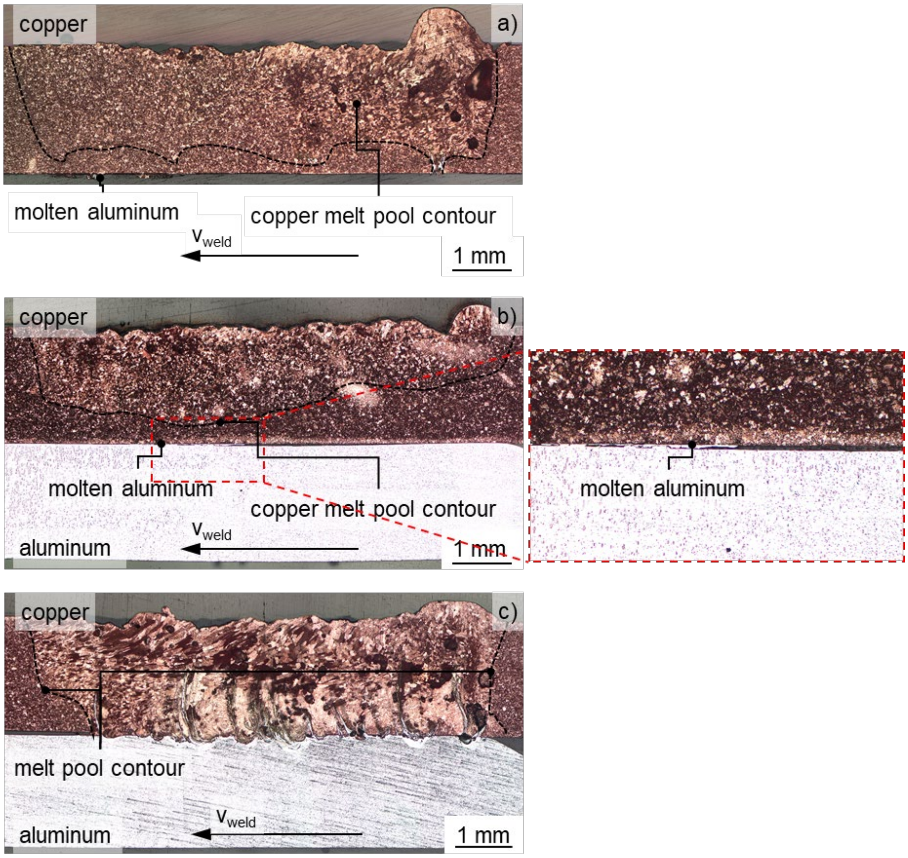

Fig. 6. Comparison of three cross sections of welding in aluminum. a) welding of aluminum copper mixing joint by using an IR laser beam source. b) molten aluminum without a common melt pool by using a green wavelength. c) Welded specimen with a common melt pool using a green wavelength.

Despite the possibility of a more stable welding process, due to the green laser wavelength, the three cross sections in Figure 6 show significantly different results. The first figure corresponds to a weld with IR laser radiation, while the last two figures correspond to welds with green wavelength. The upper figure a) shows a cross-section of a weld made with Coherent IR-ARM beam source. The minimal melting of the aluminum material can be seen on the interface of the copper. The second figure b) shows the multiple coupling of the keyhole into the lower joining partner. This can be seen by the adherent aluminum in the copper joining partner. The opposite is shown in the third figure c). The welding depth in the copper material is significantly lower. Due to the molten aluminum in the interface, it can be concluded that the melting temperature of aluminum in the interface has been exceeded. This wetting of the melt also leads to the joining of the two specimens. The first figure corresponds to a weld with IR laser radiation, while the last two figures correspond to welds with green wavelength. In the future, the stabilization of the keyhole and the control of the temperature must be optimized.

4. Conclusion

Modern beam sources offer a wide range of possibilities to realize complex processes. In particular, laser welding of copper materials involves many challenges. In this paper it has been shown that deep welding close to the interface is possible. Due to the large difference in liquidus temperature between aluminum and copper, the aluminum can be melted without forming a common weld pool in the interface. This allows the generation of a joint without the formation of intermetallic compounds. The feasibility of this approach was confirmed by the measurements of the temperature in the joining zone. Challenges arising in the formation of the joint zone, which is mainly determined by the wetting of the aluminum melt, could be shown by copper-side images of the separated joint. The transfer to a beam source emitting in the green spectrum was successful and shows the same challenges. In the future, better control of the welding process will be achieved by using laser beams with flexible beam caustics as well as detailed evaluation of the process emissions.

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