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# Laser Beam Vacuum-Welded Cu-Al Mixed Joints

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**Abstract**

A great potential for lightweight construction lies in the substitution of copper by aluminum. It is possible to apply aluminum as a conductor and copper as a contact material. During the fusion welding of this joint, brittle intermetallic phases occur which negatively affects the mechanical and technological properties of the joint. Also is the electrical resistance of most intermetallic phase's one order of magnitude higher than that of the pure Materials. External influential factors, such as temperature, current-feed and time bring about the change of the joining zone structure by diffusion and electro-migration. Moreover, a temporal change of the technological properties (further increase of the electric resistance, reduction of strength) of the dissimilar material joint will occur. Findings about this behavior will allow drawing conclusions about the expected lifetime of the joints. This paper reports on the change of properties of the mixed joints after electrical usage.

Keywords: Laser Beam Welding; Copper; Aluminium; Mixed-Joints; Singelmode Fiber Laser

## 1. Introduction

Electronics and electrical engineering are becoming increasingly important in today's mechanical engineering products. While cars, for example, had a minimum of on-board electronics in the 1980s, the trend today, in addition to electronic comfort and safety equipment, is towards a completely electrified drive. In electric cars in particular, it is necessary to pursue lightweight construction concepts for weight reduction in order to extend the range, which is currently still very low due to limited accumulator capacity. To achieve this, it is not sufficient to introduce multi-material structures in the bodywork if the weight saved is balanced out by the electrical component, Reisgen et al., 2009. Copper cables, which act as electrical

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conductors, offer considerable savings potential. Since copper has a density that is about three times higher than aluminum, a large weight can be saved by substitution, Valencia and Quested, 2008.

In its pure form (e.g. Al 99.5) aluminum has a slightly higher electrical resistance than copper. However, copper as a conductor material has significantly higher strengths with comparable electrical conductivity to aluminum Al 99.5, Meaden, 1965. For this reason, it is more suitable in this form for electrical contacts, which are usually designed as screw connections and must therefore have corresponding functional strengths. Aluminum alloys, which, in contrast to pure aluminum, are also suitable for screw connections due to their higher strength, have a significantly higher electrical resistance. Furthermore, aluminum forms an oxide layer on the surface, which increases transition resistances. The complete substitution of copper by aluminum would therefore have some disadvantages. However, it is possible to produce the cables from high-purity aluminum and the contacts from copper in order to combine the good suitability as electrical contact material of copper with the low density with comparable conductivity of high-purity aluminum. However, this requires material-locking mixed connections between aluminum and copper. In addition to friction stir welding, Lee et al., 2005, Xue et al., 2010, Tan et al., 2013, joining of Cu-Al mixed joints is now also possible by ultrasonic welding, Bermann, 2013, Zhao et al., 2013, resistance welding, Schunk, 2013, laser beam welding, Hailat et al., 2012, Mai and Spowage, 2004, and other methods, Frauenhofer IWS Dresden, 2013. This paper reports on the influence of dilution and electrical usage on the electrical properties of laser beam vacuum-welded Cu-Al-mixed joints.

Laser beam welding under reduced working pressure was first researched back in the 1980s and 1990s. The aim of this work done by Arata et al., 1985, Verwaerde and Fabbro, 1995 and Katayama et al., 2001 was to reduce the plasma plume generated by CO2 laser welding. Based on these results, work in this field started again in 2009 using modern solid-state laser beam generators (single-mode fiber lasers). In the subsequent development of the equipment and the possible applications of the process variant, remarkable results in the field of thick plate welding of steel materials were achieved, Reisgen et al., 2013. Single-pass joints up to a sheet thickness of 50 mm were realized on unalloyed steel and weld seams up to a sheet thickness of 110 mm were realized welding by the pass/capping pass method. In the field of high-alloy steel materials and nickel-base alloys, single-layer joint welds in the sheet thickness range of 30 to 40 mm have also been successfully implemented.

The results which have been obtained so far and the resonance in the industry reflect the great potential of the process. More recent research at the ISF showed that laser beam welding under reduced ambient pressure can greatly stabilize and improve welding results when welding copper at welding speeds between 0.5 and 2 m/min, Reisgen et al., 2016.

## 2. Materials and methods

### *2.1. Materials and equipment set-up*

Copper and aluminum sheets of 2 mm Thickness were used for this study. Material with a high purity was chosen. The results from the optical emission spectrometry are listed in Table 1. The specimens had a size of 100x50x2 mm. For the guarantee of a zero gap, the bevel preparations of the specimens were milled.

Table 1. Chemical analyses of base material

| Alloy | Al | Cu | Si | Fe |
|---|---|---|---|---|
| Cu | 0.0051 | 99.9 | 0.0002 | 0.0224 |
| Al | 99.5 | 0.0086 | 0.105 | 0.343 |

Acetone was used to clean the specimens from grease and impurities. Samples were welded using a FOCUS LaVa95 laser vacuum chamber and an IPG YLS-2000-SM laser with a maximum laser power of 2 kW. Beam shaping is realized outside the vacuum chamber via an IPG D50 welding head with 2-D beam oscillation. A beam size of 70 µm was used. 1200 W laser power and a welding speed of 1.5 m/min were used. The trials were conducted at a work pressure of 100 mbar. Reducing the work pressure showed a great influence on the process stability when welding copper or aluminum. For this reason and to minimize oxidation during welding the laser beam under vacuum (LaVa) process was used. In order to change the dilution of the mixed material join by melting less copper, the focal position of the laser beam was changed parallel to the welding direction as seen in Fig. 1.

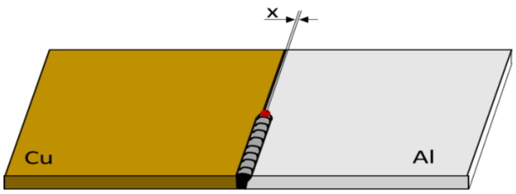


Fig. 1. Schematic representation of LBW process and focal off-set

### *2.2. Long-term behavior*

Electrical components, which usually consist of aluminum or copper, have an operating temperature of about 100 - 150 °C, at peak loads even up to 200 °C, Schmidt et al., 2012. At this temperature, diffusion processes begin for mixed connections made of aluminum and copper, Lee et al., 2005.

Investigations on bolted aluminum-copper conductor rails show that diffusion mechanisms have obviously led to formation of intermetallic phases at an ageing temperature of 140 °C. Joint resistance measurements over the outsourcing period showed a significant increase, which was not observed for similar Al-Al and Cu-Cu compounds, Schneider et al., 2009

The temperature-related changes in the intermetallic phase seam of welded joints were investigated in several projects, Lee et al., 2005 and Schneider et al., 2009. A growth of the intermetallic phase was always observed.

Beside the temperature also the influence of the electrical usage of the joint needs to be considered when looking at the long-term changes of the joint. In order to investigate the influence of the electric current on the resistance of the mixed joint a test stand was constructed, Fig. 2. The Test setup allows running a current of up to 210 A (maximum continuous loads usual in operation of electrical conductors) through up to 20 specimens in a serial circuit.

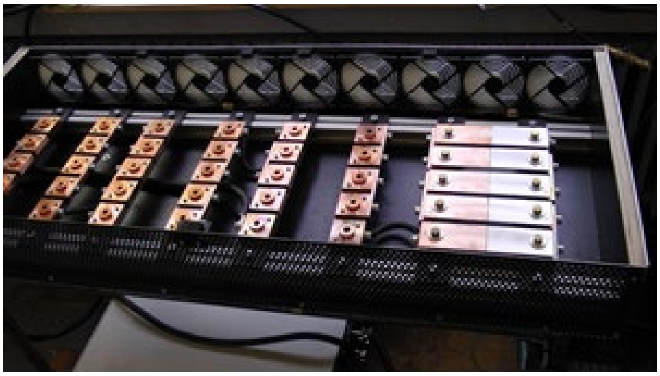

Fig. 2. Test stand for running a long-time current

During the test, the specimens can be cooled by air or if necessary by water cooling the sample mounts.

## 3. Results

The joining zone of the fusion welding process is always similar. Fig. 5 shows a laser beam weld under vacuum (1200 W; 1.5 m/min; surface focus) in back-scattered-electron (BSE) mode. The three recognizable areas are the two base materials aluminum (left) and copper (right), as well as the weld seam, which is delimited on the aluminum side by the fusion line and on the copper side by a fine seam. Suture imperfections such as pores or cracks cannot be detected. With increasing magnification, more areas become visible, Fig. 3 b). On the left in part b, the area is saturated with a maximum copper concentration of 3 at%. This aluminum-rich phase is interspersed with copper-rich dispersions. The area M can therefore be identified as an aluminum solid solution (α-Al), similar to an EN-AW-2xxx alloy. In addition to the area M, a very fine lamellar structure is visible, which is typical for eutectic solidification. With EDX area measurements, which have a concentration range of 19.9 at.% - 22.5 at.% Cu, this phase can be identified as the eutectic (E) of aluminium solid solution and $Al_2Cu$ (θ phase). The intermetallic phase (I) shows on the copper side a fine seam consisting at least of the phases $Al_2Cu$ (θ phase).

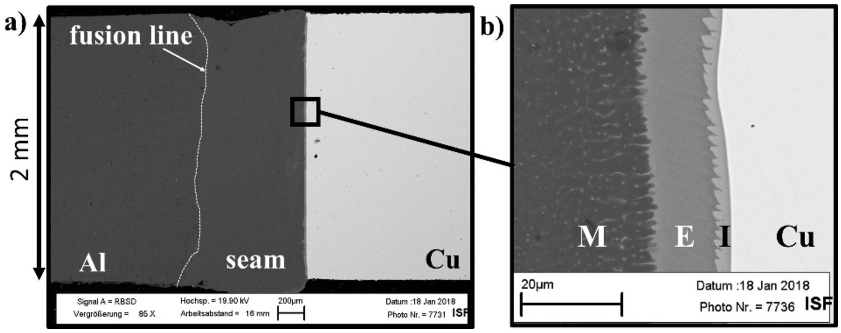


Fig. 3. BSE analysis of laser beam under vacuum Al-Cu joint (a) full cross-section (b) magnification of intermetallic phase seam

The measured resistance Rv for welds with different degrees of dilution (realized by applying an off-set of the laser beam) can be seen in Fig. 4. A positive off-set was defined as an off-set towards the aluminum side. If welded with an off-set towards the copper side, the weld seam showed cracks. An off-set of more than 0.4 mm towards the aluminum side resulted in no connection at all.

Even though the most intermetallic phases in an Cu-Al-system show an electrical resistivity 5-8 times greater than the pure elements, Rayen et al., 1980, the resistance of weld seams (if a connection is achieved) shows a value between that of the pure base materials, Fig. 4. Even though EDX area measurements show a decrease of Cu in the area M of the weld seam with increasing off-set, the resistance of the weld seams varies only little.

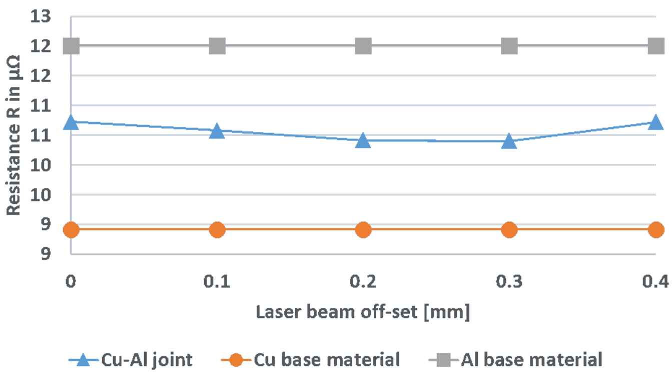


Fig. 4. Average resistance over laser beam off-set

As seen in Fig. 5, the beam off-set influences the intermetallic phase seam only slightly. More notable is a slightly wider eutectic phase and a much wider mixed crystal (α-Al) with less Cu dispersions. Also notable is the strait fusion line on the copper side.

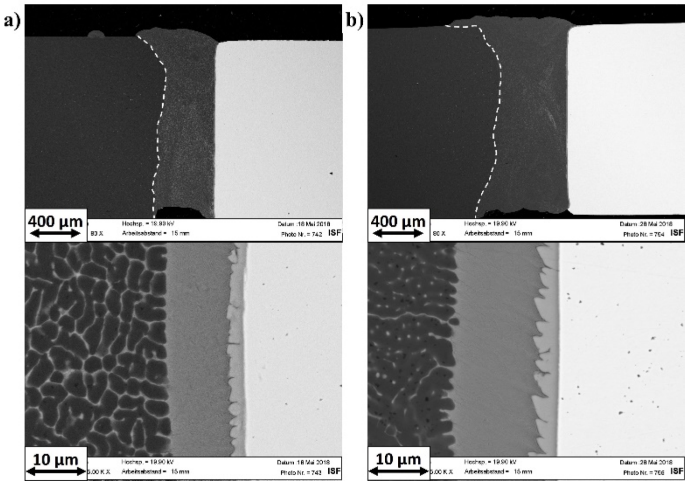


Fig. 5. BSE analysis of laser beam under vacuum Al-Cu joint (a) off-set= 0,1 mm; (b) off-set= 0.3mm

In order to determent the influence of a current on the resistance of the welding connection specimen with different off-sets were welded (connecting area of 80 mm²), mounted in the test stand (see Fig. 2) and put under a current of 200 A for 2 weeks. The resistance was measured right after the welding, after one week and then again after week two. The results can be seen in Fig. 6.

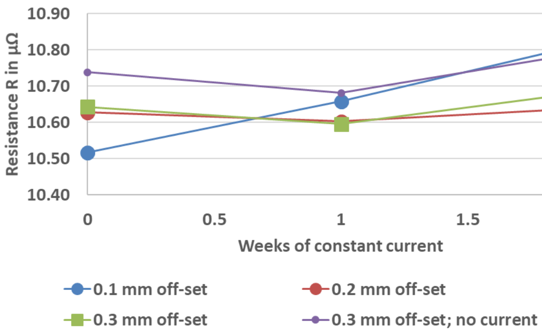


Fig. 6. Average resistance over weeks of constant current

It is notable that for most specimen at first a decrease of the resistance was observed, when applying a current. After the second week most subjects showed an increase in resistance, thus a worsen of the electrical properties of the joint. This behaviour could also be observerd with specimen that did not undergo the electricla testing.

In Fig. 7, the backscattering electron microscope images of two cross sections can be seen. The left (a) cross section shows a connection weld without running a current, while the right (b) specimen was tested with a current of 200 A as described above. It can be seen that in both cases most of the weld seam consists mainly of an oversaturated aluminum mixed crystal consisting of Al and 4 at.% Cu.

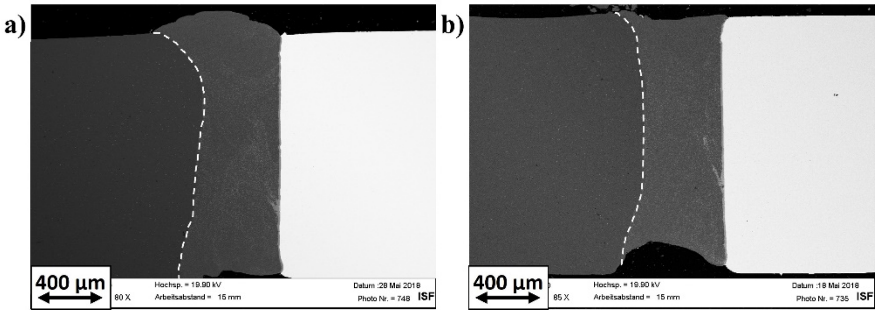


Fig. 7. BSE analysis of laser beam under vacuum Al-Cu joint; off-set 0.3 mm; scale= 400 µm; (a) without electrical usage; (b) with electrical usage

Fig. 8 is a 5000x magnification (scale: 10 µm) of the intermetallic phase seams on the copper side of the welds. The tested specimen put under an electrical current for two weeks (Fig. 8 b)) show no notable growth of the intermetallic phase seam compared to the weld seam without electrical load (Fig. 8 a)). In both cases, an approx. 13 µm thick eutectic phase was observed. A growth of this phase was not detected. EDX measurements indicate that region E has a copper content of 18 at. % in both cases. This phase is identified as the eutectic region of aluminum solid solution and Al2Cu (θ phase).

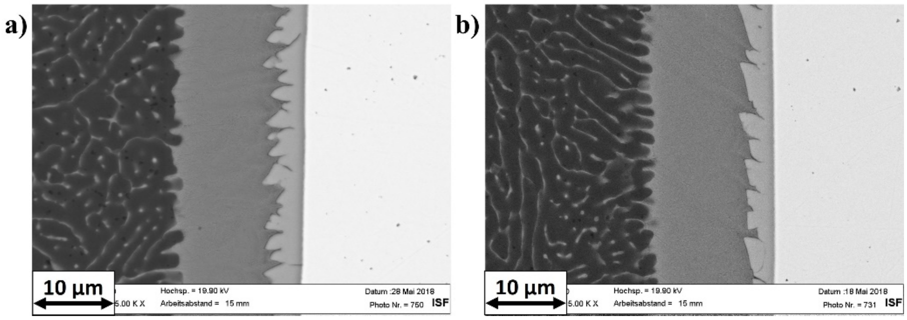


Fig. 8. BSE analysis of laser beam under vacuum Al-Cu joint; off-set 0.3 mm; scale= 10µm; (a) without electrical usage; (b) with electrical usage

Merely a difference of the copper rich dispersions and the transition from the M area to the E area can be observed.

The evaluation of the tensile tests is shown in Fig. 9 (left). The maximum tensile strength of 90 MPa was achieved with a beam offset of 0.3 mm. Almost all tensile specimens failed in brittle fracture with a maximum elongation of 1.5 %. In the tests with 0.3 mm, a failure in the heat affected zone of the aluminum occurred sporadically, Fig. 9 (right). From a distance of 0.5 mm the copper sheet is no longer completely melted and a joint is formed which consists of a weld seam on the aluminum side and a solder joint on the copper side.

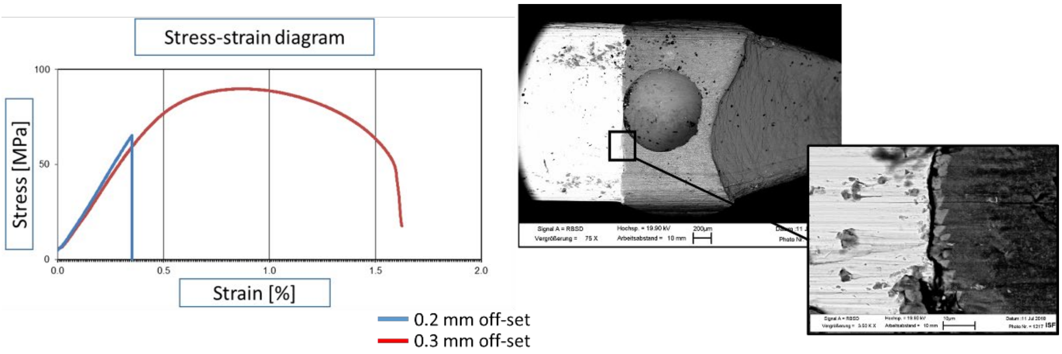


Fig. 9. Stress-strain diagram (left); EBS analysis of laser beam under vacuum Al-Cu joint; off-set 0.3 mm; Cu-Weldsam-Al; scale= 200 µm; magnification of intermetallic phase seam; sacale= 10 µm (right)

Almost all tensile specimens failed in brittle. Both fracture surfaces of a specimen with a distance of 0.4 mm are shown in Fig. 10 left.

At least two different copper- aluminum ratios could be observed. In Fig. 10 right the main measured copper content is 35-40 at.% on both the copper and aluminum sides. This means that the fracture at this point passes through the intermetallic phase $Al_2Cu$. The smaller phase, again present on both sides, show a copper content of 51-53 at.% which means the intermetallic phase AlCu is present there. The crack can therefore run in the boundary layer between the $\eta_2$ and $\theta$ phases.

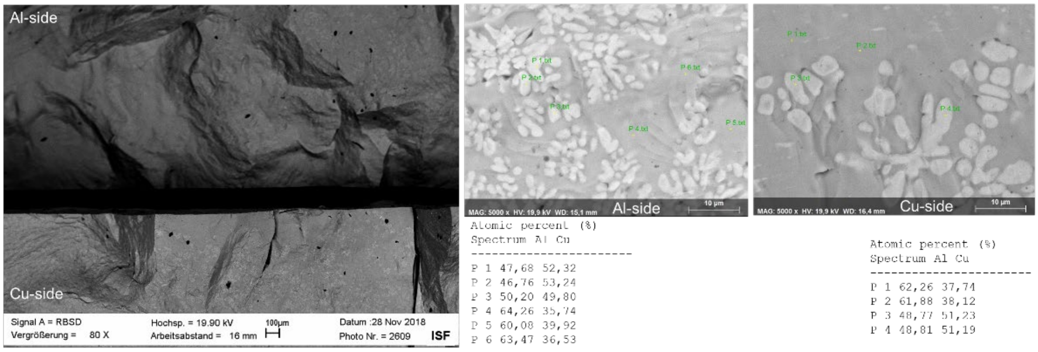


Fig. 10. Fracture surfaces; scale= 100 µm (left); EDX measurements of fracture surfaces; scale= 10 µm (right)

## 4. Conclusion

Sound welds of the material combination aluminum-copper were produced by laser beam welding under reduced ambient pressure. All connections showed an electrical resistance between that of the base materials. Due to the concentrated energy input of the high-power laser beam, the total heat input can be controlled which directs to short interaction times. Thus, an uncontrolled formation of brittle intermetallic can be avoided. The trials done in this work all show very small narrow weld seams with a very low content of copper. The reason for that most probable is the fact, that aluminum and copper show different absorption rates for infrared laser energy. The laser intensity and energy per unit length used in this work was high enough to melt the aluminum base material but was almost totally reflected by the copper. This presumption is supported by the fact that the fusion line on copper side is a straight line (joint preparation) and the weld seam area increases when using a beam off-set towards the aluminum side (Fig. 5). Even though the overall dilution rate of the weld seam could be influenced by using a laser beam off-set (melting more aluminum) the electrical properties of the weld seams stayed the same.

All laser welded copper aluminum mixed joints showed very good electrical properties. Even welds with very thick intermetallic phases showed good electrical properties.

Only when widening the weld seam by using a beam oscillation a significant increase of resistance (up to two times the resistance of aluminum) could be observed.

Since at the tested beam intensity and welding speed no deep penetration welding of the copper was observed, the beam power should be increased in order to increase the copper content of the weld seam and thereby to further investigate the influence of dilution in the weld seem on the connection resistance.

After running a current of 200 A through the specimen at first a decreasing and then an increasing of the connection resistance Rv was observed with no notable change of the intermetallic seam or the eutectic phase (Fig. 6). Merely a difference of the copper rich dispersions and the transition from the M area to the E area can be observed (Fig. 8). These tests must be repeated in order to confirm the results. Further more these results should be viewed with caution since the change is very small and could also be accounted for by measuring inaccuracy. In the next tests the connection area will be decreased in order to test at a higher current density. This far a growth of the intermetallic phase could not be observed after applying a current for two weeks. In the next steps, the current density and the testing time will be increased.

The investigation of the long-term behavior of welds under the influence of current is of interest for the field of application of electrically conductive connections and should be investigated further. The temporal changes, especially in a complete view of the joining zone and the mechanical properties of the weld seam are currently not sufficiently documented.

Corrosion can be a problem due to the large difference in the standard electron potential of copper and aluminum. The effect of corrosion on the welded joint must therefore be investigated.

In addition, the physical properties of these mixed connections should not be neglected. Due to the brittleness of the intermetallic phases, it was difficult to examine bad specimen. For application purposes physical properties like hardness and ductility needs to be investigated and optimized.

## 5. Acknowledgements

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