

Investigation and Improvement of dissimilar Aluminum-Copper Joining using Magnetic Pulse Welding combined with local Inert Gas Application

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Abstract

Well-performing electrical conductors and contacting processes are crucial for a variety of industries and applications, including flat conductors such as busbars. The challenge is to manufacture relevant systems with excellent properties in a cost-efficient and ecological way. From a materials science perspective, one approach could be the utilization of aluminum in electrical systems. This is because aluminum is a better conductor than copper with regard to its weight. However, the exclusive use of aluminum is limited by the constraints of electrical systems that require the partial use of copper. This can be due to space limitations or connections to the power electronics, which are predominantly copper components. Hybrid systems consisting of aluminum, copper and dissimilar joints between both materials have been identified as a viable solution. However, the fabrication of these joints is challenging for conventional fusion welding processes due to chemical and thermophysical incompatibilities. Magnetic Pulse Welding (MPW) is a solid-state welding process which, due to its characteristic low energy input, allows a resource efficient fabrication of dissimilar joints. However, the limitations of MPW and their expandability, its potential for future applications, and the interactions of the process parameters with observed joint properties have not been sufficiently researched. Consequently, this study addresses MPW in the field of joining flat conductors by investigating the correlations between process parameters and mechanical, microstructural, and electrical joint properties. Furthermore, an inert gas supply during joining is investigated in order to determine the potential for improvement of the weldability and the resulting joint properties.

Keywords

Magnetic Pulse Welding, Dissimilar Materials, local Inert Gas Application, Electrical Joint Characterization

1 Introduction and state-of-the-art

Electrical contacts are becoming increasingly important. The possibility of using aluminum instead of copper as a conductor increases economic efficiency through cost and weight savings (Kaspar et al., 2014). Nevertheless, systems consisting only of aluminum are currently still not conceivable. For example, one problem is that components of power electronics are made of copper or that busbars consist of both aluminium and copper to be suitable to handle Li-ion battery packs (Schmidt et al., 2012). Therefore, a contacting process for aluminum-copper joints must be established. The contacting process should ideally be material-locking in order to ensure long-term reliable joints (Schmidt et al., 2012). This is where magnetic pulse welding (MPW) as a solid state welding process provides a solution. Many studies have shown that aluminum-copper-joints can be realized using the collision based process MPW. The MPW imminent collision is initiated by a current flow in a coil, which is generated by a controlled capacitor discharge. This current flow generates a magnetic field that induces eddy currents in a well-conducting adjacent joining partner (flyer). The eddy currents interact with the primary magnetic field, resulting in a force that accelerates the flyer. The flyer is purposefully brought into collision with the secondary joining partner, the target, after a few millimetres. The collision occurs as a rolling movement of the flyer on the target. The collision angle and collision speed vary continuously. If the collision angle and speed are within specific ranges, a mass flow, the jet, consisting of the boundary layers of both joining partners, atmospheric components and surface impurities, emerges from the collision point. This results in a welded joint between the bare metal surfaces of the two joining partners. (Graß et al., 2024) In the field of MPW of aluminum and copper this applies both to sheet-to-sheet joints (Psyk et al., 2017) and to tubes that are welded with other tubes (Wu and Shang, 2014), rods (Hokari et al., 1998; Marya et al., 2005; Oliveira et al., 2017; Raelison et al., 2014) or cables (Graß et al., 2024).

The electrical properties of these joints were investigated for sheet-to-sheet and tube-to-cable joints (Graß et al., 2024; Psik et al., 2017). It was found that joints with good mechanical and electrical properties could be produced. In the studies by Pabst and Groche, the potential for MPW process improvement by influencing the ambient medium was investigated (Pabst and Groche, 2018). It was demonstrated that especially helium in the joining gap has a process-improving effect.

This study aims to address these findings by investigating an easy-to-implement method of enhancing the quality of MPW for aluminium and copper. A nozzle-based inert gas application was developed that significantly improves the quality of MPW joints, particularly in the area of the lower process boundary.

2 Materials and experimental methodology

2.1 Materials

Aluminum and copper alloys with good electrical properties were selected for the present investigation. The materials are specified in **Table 1**. The utilized sheets were 100 mm long

and 40 mm wide. The sheet thickness was 1 mm for copper and 1.5 mm for aluminum. These sheet thicknesses were used to partially compensate the different electrical conductivity coefficients. Before welding, all joining partners were cleaned using isopropyl.

Alloy	Tensile strength [MPa]	Electrical conductivity [MS/m]
AA1050A	106	34,15
Cu-ETP	269	59,24

Table 1: *Materials used for the investigation*

2.2 Experimental setup and welding parameters

All fabricated joints were welded with a BlueWave PS48-16 system from PSTproducts GmbH. The utilized single turn sheet welding coil features an active area of 80 mm x 10 mm and a thickness of 4 mm. The positioning of the joining partners above the active area of the coil, the GFRP spacers used to adjust the acceleration distance and to define the overlap of 30 mm and the positioning of the inert gas nozzle are shown in **Fig. 1**. The hold-down-device is not illustrated. It is fastened prior welding using the four visible bolts. Helium is used as the inert gas, the flow rate is 8 l/min. The experiments were conducted with and without an inert gas flow. The acceleration distances were 1.5 mm and 2.5 mm. The discharge current was varied in three increments: 232 kA, 321 kA and 392 kA. The system frequency for all experiments was 19,9 kHz. AA1050A was always used as the flyer, as researchers have demonstrated that better electrical and mechanical joint properties can be achieved in this way (Psyk et al., 2017).

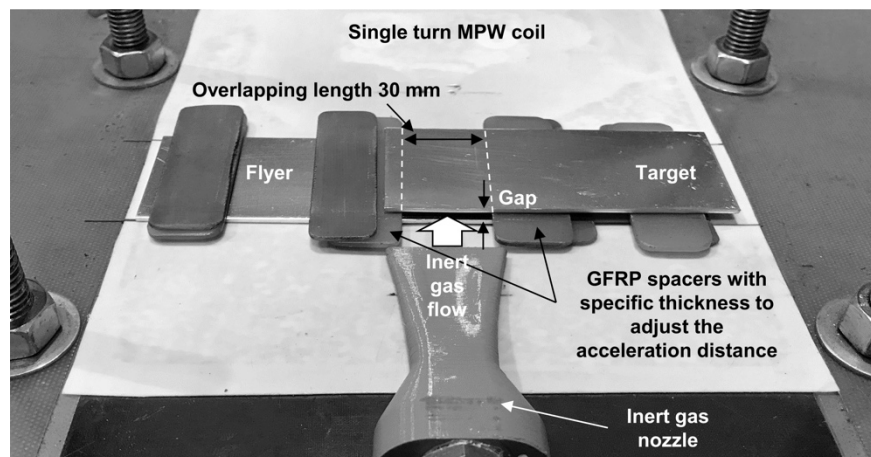


Figure 1: *Experimental setup of MPW with inert gas nozzle. Overlap area centered over the active coil area and defined using markings and GFRP spacers.*

2.3 Mechanical characterization

The welded joints were tested quasi-statically using a universal tensile testing machine (Z100, ZwickRoell GmbH & Co. KG). The test speed was 5 mm/min. No shims were used,

but the clamps were adjusted according to the acceleration distances and sheet thicknesses. After the mechanical testing, the determined maximum force was used for further evaluation. The mean, the minimal and the maximal values from three tests for each parameter variation were considered for the determination of the mechanical joint quality. The location of the failure was also documented. If all samples of a parameter variation fail in the base material, this is indicated in the diagram as a "base material" failure location.

2.4 Electrical characterization

All welded joints were examined using the four-wire Kelvin measurement method according to **Eq. (1)**. The resistance of a joint ($R_{Measurement}$) was determined based on the measured voltage difference (ΔV) and the applied constant current (I) of 50 A. For the evaluation, the measured value of the respective joint was divided by the mean value (R_{Ref}) of the resistances of the two pure joining partners, see **Eq. (2)** and **Eq. (3)**. All values lower than one are consequently better than the electrical quality of the pure sheet materials. This is possible because the MPW joint is a lap joint. Thicker conductor cross-sections can therefore be present in the overlapping and welded area. To characterize the electrical properties of the joints, five samples for each parameter variation were utilized, and the mean, minimum, and maximum values were determined.

$$R_{Measurement} = \frac{\Delta V}{I} \quad (1)$$

$$R_{Ref} = \frac{1}{2}(R_{Al} + R_{Cu}) \quad (2)$$

$$R_{Calc} = \frac{R_{Measurement}}{R_{Ref}} \quad (3)$$

An MR5-200C micro-ohmmeter (Schuetz Messtechnik GmbH) was used as the measuring device. The distance between the voltage tapping points was 50 mm for all experiments.

2.5 Analysis of weld seam geometry and microstructure

For the investigation of the microstructure after MPW, the investigated joints were cut longitudinally in the middle of the deformed area using a wet cutting grinder. The samples were embedded in cold-curing acrylic resin (ClaroCit from Struers GmbH), ground to a grain size of 4000 and polished with diamond suspension (grain size 1 μm). The samples were examined using scanning electron microscopy (SEM, Zeiss SEM ULTRA PLUS) and energy dispersive X-ray analysis (EDS, Bruker 6|60). The SEM was operated with a voltage of 20 kV, the working distance was 10 mm and images were captured using the SE2 detector.

The weld seam geometry was analyzed by dissolving the aluminium of welded joints with a sodium hydroxide solution (10 mass% over a period of 24 hours). The remaining weld

seam was subsequently examined and quantified from a top view using a microscope (Leica Z16).

3 Results and discussion

The fabricated joints were characterized with regard to their electrical and mechanical joint quality. **Fig. 2 a)** shows the mechanical and **Fig. 2 b)** the electrical joint quality as a function of the MPW process parameters and the ambient atmosphere. The effect of the inert gas helium in the acceleration gap on the mechanical joint quality is particularly evident in the range of low discharge currents. Joints manufactured with 232 kA without inert gas withstand hardly any forces in the quasi-static tensile shear load case. The same attempts with inert gas in the acceleration gap enable the fabrication of joints that can withstand more than 4 kN in the same load case. In both cases, the failure occurs in the weld seam. Increasing the discharge current to 321 kA or even 392 kA results in a failure in the aluminum base material regardless of the adjusted gap and the atmosphere inside. Similarly, the electrical joint quality in the range of low discharge currents (here 232 kA) is also strongly influenced. The application of an inert gas causes an improvement in this case, so that a result of almost one is obtained. In the range of larger discharge currents, the inert gas has no significant effect on the electrical joint quality. However, the MPW process parameters have an effect on the electrical joint quality. An increase in the discharge currents from 321 kA to 392 kA results in an improvement in the joint quality. The gap likewise has an impact. Joints produced with a gap of 1.5 mm and 321 kA discharge current perform electrically superior to joints produced with 321 kA and a gap of 2.5 mm.

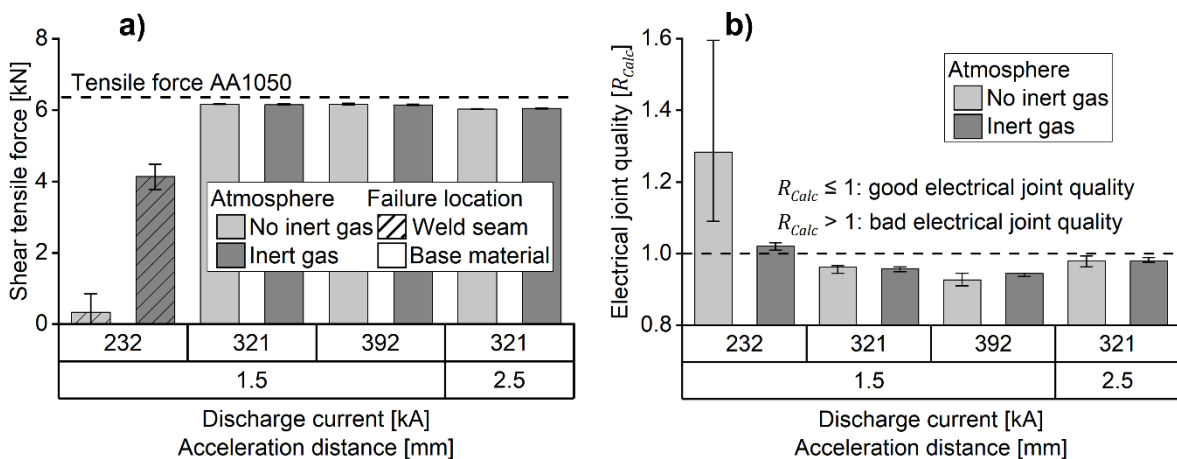


Figure 2: a) Quasi-static shear tensile strength (mean, minimum, maximum) and failure location and b) electrical quality (mean, minimum, maximum) of joints with regard to the applied discharge current (x-axis top line) and the gap prior welding (x-axis bottom line).

To investigate the influence of the inert gas on the mechanical and electrical quality of the joint, the geometry of the weld seam is analyzed. **Fig. 3** shows the top view of weld seams fabricated with different gaps and varying discharge currents with and without inert gas.

In both cases, the inert gas affects the size of the weld seam. In the case of 1.5 mm gap and 232 kA discharge current, the inert gas application results in the complete formation of the weld seam and consequently a significant increase of the weld seam size. This goes alongside the findings on the mechanical and electrical properties of these joints, compare **Fig. 2**. In the case of a 2.5 mm gap and a discharge current of 321 kA, the inert gas causes an enlargement of the weld seam. However, the electrical and mechanical joint properties are not affected, as **Fig. 2** reveals. A possible reason is that the weld seam is already adequately large without inert gas and therefore enables excellent electrical joint properties. The determined area of 67.4 mm² is already larger than the 60 mm² cross-section of the aluminum joining partner.

In order to further investigate the effects of the inert gas on the weld seam formation, the subsequent step consists of analysing cross-sections using SEM. **Fig. 4** shows images of joints fabricated using 321 kA discharge current and 2.5 mm gap with and without inert gas during MPW. **Fig. 4 a)** shows the beginning of the weld seam of a joint welded in an inert gas atmosphere. An MPW typical wavy but non-turbulent interface between the aluminum and copper joining partners is present. A material-contiguous joint was formed between aluminum and copper, as shown by an EDS line scan through a melt pocket near the beginning of the weld. Furthermore, no increase in oxygen was detected, indicating that the jet was able to be completely emitted out of the collision point.

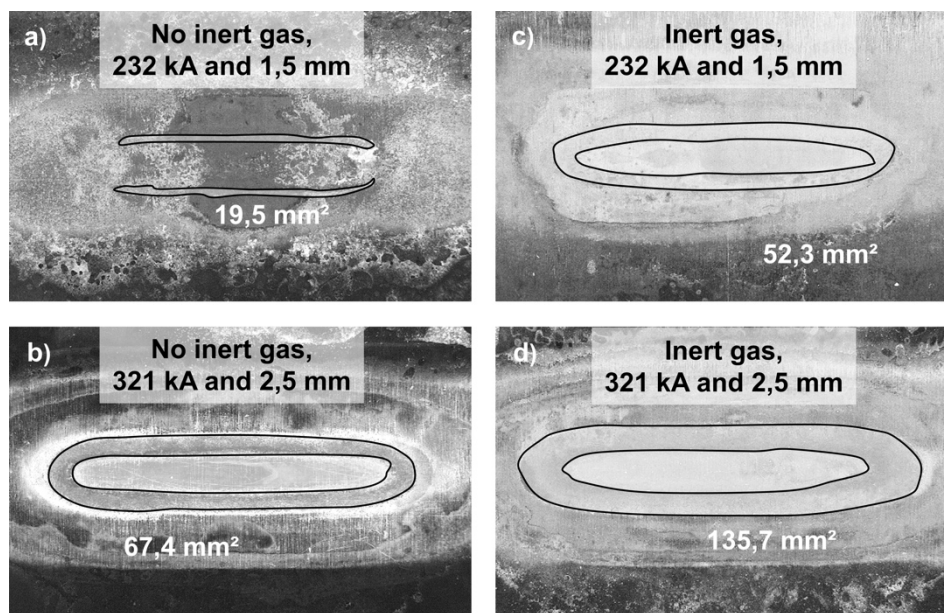


Figure 3: Top view of MPW weld seams joined using different process parameters, with and without a nozzle-based application of inert gas during welding.

A weld seam fabricated with a gap of 2.5 mm and a discharge current of 321 kA without inert gas exhibits entirely different properties at the beginning of the weld seam. A region characterized by the presence of pores and cracks is observed in proximity to the weld seam. This suggests that the joining partners have enclosed the jet through their collision or have at least interacted strongly with it, thereby preventing the complete emission of the jet from the collision point. The EDS line scan in the respective weld seam area corroborates this

finding. An increase in the oxygen content is observable. This finding suggests that incomplete emissions from the plasticized joining partner boundary layers, particularly the aluminum oxide layer, may be a contributing factor.

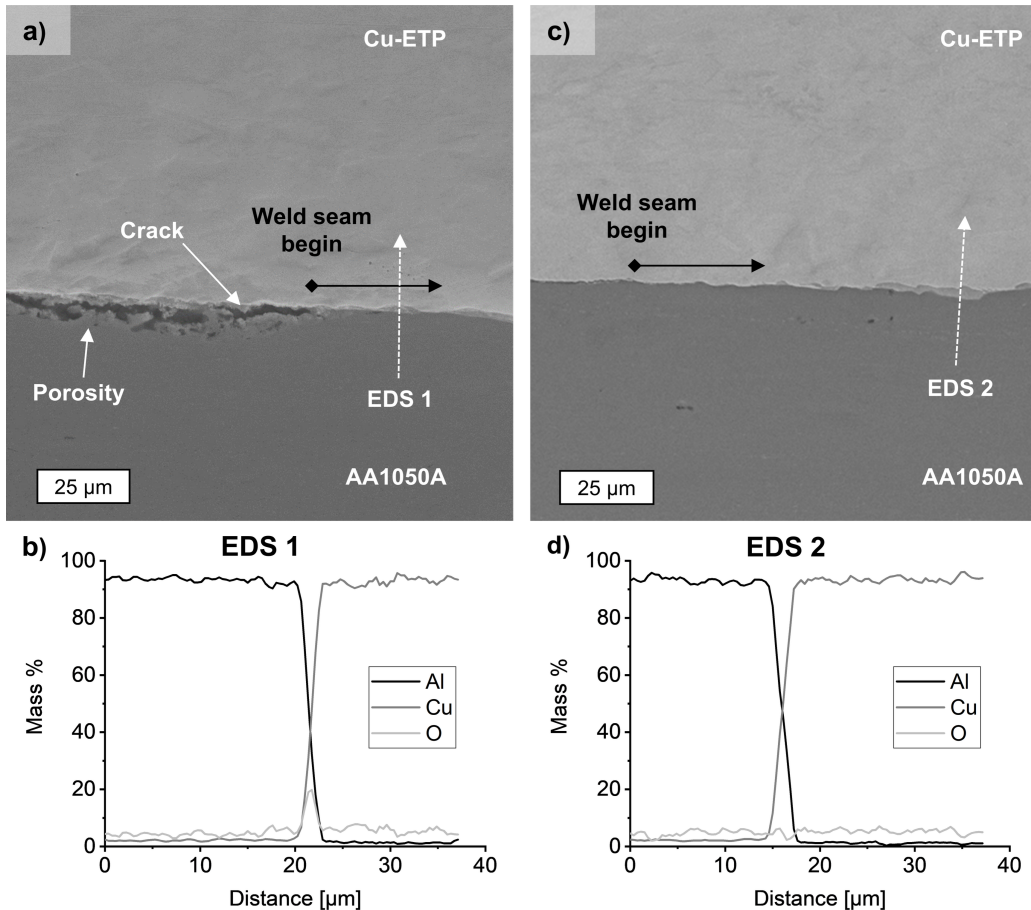


Figure 4: a) SEM image of the beginning of the weld seam and the position of EDS 1 line scan of a joint fabricated using 321 kA discharge current and a 2.5 mm gap without inert gas supply, b) result of EDS 1 line scan, c) SEM image of the beginning of the weld seam and the position of EDS 2 line scan of a joint fabricated using 321 kA discharge current and a 2.5 mm gap with inert gas supply, d) result of EDS 2 line scan.

4 Conclusion and Outlook

Hybrid aluminum-copper joints could be manufactured using MPW in a broad range of process parameters. Appropriate evaluation methods enabled the joints to be confirmed as featuring good mechanical and electrical properties. Interactions between the electrical and mechanical joint properties, the MPW process parameters and the ambient atmosphere created by a nozzle-based approach were successfully investigated. It has been proven that a nozzle-based application of the inert gas helium in the range of the lower process limit is associated with a substantial increase in joint quality. The reason is attributed to the influence of the inert gas helium on the jet. A detailed analysis of the microstructure revealed that the

presence of an inert gas within the joining gap enabled the jet to emerge from the collision point unimpeded, devoid of any interaction with the joining partners.

A thorough analysis is necessary to ascertain the precise impact of the inert gas on the processes occurring within the joining gap. A crucial aspect that necessitates investigation is the influence of the inert gas present within the joining gap on the exothermic reaction of the boundary layers of the joining partners during their collision. A further examination of the interactions between the deformation and the resulting velocity of the flyer and the atmosphere in the joining gap is also warranted. In addition, the targeted fluidic influence of the jet by an optimized inert gas nozzle should be investigated. Furthermore, a spatially resolved analysis of the joint properties might be conducted to investigate the interactions between the local microstructure, its manipulability using inert gas during welding, and the resulting global electrical, mechanical and corrosion properties of the joint.

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