Manufacturing of Hybrid Aluminum Copper Joints by Electromagnetic Pulse Welding – Identification of Quantitative Process Windows

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Abstract.} Compared to conventional joining techniques, electromagnetic pulse welding offers important advantages especially when it comes to dissimilar material connections as e.g. copper aluminum welds. However, due to missing guidelines and tools for process design, the process has not been widely implemented in industrial production, yet. In order to contribute to overcoming this obstacle, a combined numerical and experimental process analysis for electromagnetic pulse welding of Cu-DHP and EN AW-1050 was carried out and the results were consolidated in a quantitative collision parameter based process window.

MOTIVATION AND APPROACH

Excellent thermal and electrical conductivity as well as high chemical resistance make copper one of the most applied materials especially in the fields of heating and cooling and in electrical applications. However, it is also a high cost material and features high density leading to heavy components and contradicting with the demand for lightweight solutions. To provide a compromise that allows exploiting the advantages of copper without fully accepting the drawbacks, the JOIN’EM project, which is funded by the European Union, focusses on substituting components completely made of copper by hybrid copper-aluminum parts, in which copper is applied where it is indispensable, only.

Since the aluminum price is about 40\% and its density is about 30\% but the thermal and electrical conductivity are about 60\% of the according values of copper, high saving potential exists. However, the described approach requires a technology for an economic manufacturing of high-quality aluminum-copper-joints. Here, electromagnetic pulse welding, an impact welding technology offers a lot of advantages: The joint is formed due to the high velocity collision of the joining partners without noteworthy heating of the part and temperature related problems such as heat distortion, reduced strength in the heat affected zone, and formation of intermetallic phases are avoided [1]. Shielding gases and additives are unnecessary. The process can be applied flexibly because tool and workpiece geometry are only loosely related to each other. Reproducibility and automation potential is high, process times are short, and energy consumption is low.

The process principle was initially suggested by Lysenko et al. [2] in 1970. In the beginning the focus of investigations related to this process were focused on welding tubular parts. However over the last two decades also electromagnetic pulse welding of sheet metal components attracted more and more notice. Aizawa was among the first researchers deeply investigating this process variant [3]. A detailed review of the process and the developments can be found in [4].

Over the years, the feasibility and the advantages of the process have been shown for various material combinations, which are of interest for different industrial sectors. For example electromagnetic pulse welding of aluminum-steel-joints was analyzed for sheet metal parts in [5] and for tubular components in [6] and magnetic
Pulse welding of aluminum-titanium-joints was considered for sheet metal components in [3] and for tubes in [7]. Nevertheless, lacking guidelines for process, joint, and tool design have been preventing an industrial breakthrough of the technology up to now. The current work contributes to qualifying electromagnetic pulse welding for industrial implementation and making process advantages industrially exploitable by carrying out a combined experimental and numerical process analysis and presenting the results as a quantitative process window.

In electromagnetic pulse welding the directly adjustable process parameters – i.e. mainly the capacitor charging energy but also geometric parameters of the tool and the setup and in some cases the capacitance of the pulsed power generator – are not ideally suitable for defining a generally applicable process window, because quantitative conclusions regarding these parameters are valid for the regarded equipment and setup only. This means that e.g. using another pulsed power generator or tool coil will most likely require different parameter values in order to come to the same welding result. Therefore, in literature frequently the collision parameters – i.e. the impact velocity and angle – are used for sketching a process window, which is independent from the equipment and the specific setup, but usually these parameter windows are defined qualitatively only [8,9].

Contrary, in this work quantitative data is provided for welding copper (specifically Cu-DHP) and aluminum (specifically EN AW-1050). With regard to the described overall aim of the JOIN’EM project, in principle only welding of copper flyers to aluminum targets is relevant, but in order to get deeper knowledge about the transferability of the process window, welding of aluminum flyers to copper targets was regarded, too.

For quantifying the parameter window, local collision parameters must be identified. For this purpose, a coupled electromagnetic and structural mechanical simulation is performed using LS-Dyna. (For details about the simulation tool see [10]). Reasonable input data for this numerical study is gathered experimentally. This includes specifically

- the mechanical material properties of the joining partners determined by quasistatic and high-speed tensile tests,
- the measured electrical conductivity of the joining partners and the coil conductor material, and
- the coil current measured during electromagnetic pulse welding experiments.

Additionally, electromagnetic pulse welding experiments are evaluated with regard to the weld quality. As shown e.g. in [11], a joint produced by electromagnetic pulse welding consists of non-welded and welded sections. Therefore, local collision parameters and the exact position of the welded sections must be correlated to each other in order to obtain quantitative process windows.

### NUMERICAL DETERMINATION OF THE COLLISION PARAMETERS

The model was set up in LS-DYNA due to the sophisticated FEM-BEM electromagnetic solver which is well suited for problems featuring large deformations of parts from the EM domain and is particularly suitable for the coupling to the mechanical domain. The explicit mechanical solver of LS-DYNA has proved its capability to handle the existing high speed impact contact problems in EMW. The EM domain consists of the coil conductor, the flyer and the base and is completed with the remaining parts which are solely considered by the mechanical solver, specifically the positioning elements spacer and support. Insulation and housing elements have been disregarded and the coil conductor was simplified as a rigid body in these simulations.

The discretization size was adapted in the coil winding and the flyer part in order to consider the current field distribution and penetration depth of the EM field correctly. The characteristic mesh size close to the highest current density is between 0.15 mm and 0.32 mm. The skin depth at the relevant frequencies of the discharging current (i.e. 21 kHz up to 23 kHz) is about 0.57 mm for the copper alloy Cu-DHP, about 0.76 mm for the aluminum alloy EN AW-1050. Prior investigations have show that two elements over this distance are sufficient for an accurate spatial EM discretization. One more important point is the EM update timestep, i.e. the recomputation of the EM FEM and BEM system which is mandatory owing to the large mechanical deformations and the influence of this deformation to the EM domain. A negligence of the updating leads to an overestimation of the acting Lorentz forces. A frequency of the coil current between 21 kHz and 23 kHz requires an EM update timestep of at least 2 µs.

Fig. 1 depicts the numerical model including relevant geometrical parameters. Here, parameter values, which were fixed in the study, are quantified, while parameter values, which were subject to variation, are indicated by a variable. The parameter ranges regarded in the analysis are listed in Table 1. In order to reduce the experimental and numerical effort of the analysis, a D-optimal design of experiments was used for selecting parameter combinations to be regarded in the analysis. In total 26 parameter combinations were considered.
As a result of the numerical simulation, the temporary course of the deformation of flyer and target is received. In Fig. 2 exemplary forming steps are illustrated and the final geometry determined via numerical simulation is compared to the according experimental result – more precisely an embedded cross section of an electromagnetic pulse welded joint – proving the good agreement of simulation and experiment and serving as validation of the simulation.
The illustrated process states clearly how the flyer sheet is bent towards the target and hits the target at high velocity. Due to this high speed impact the flyer is rapidly decelerated and the target sheet is deformed. The significance of this deformation depends on the kinetic energy of the flyer sheet as well as on the strength of the target. Typically, welding of aluminum flyers to copper targets, which features higher strength compared to the aluminum, leads to moderate target deformations, while welding of copper flyers to aluminum targets can cause remarkable deformation of the target in form of a thickness reduction. The impact angle \( \alpha_{\text{impact}} \) obviously depends on the deformation of both, flyer and target. During the ongoing process, the flyer aligns to the target. Thereby, the local impact angle and impact velocity vary with the impact position.

More detailed information about these collision parameters can be gathered from Fig. 3, which exemplarily illustrates typical local distributions of the impact velocity (more specifically the velocity component, which is directed normally to the target surface) and the impact angle for welding of copper flyers to aluminum targets and vice versa. In both cases the flyer edge \((d=0\,\text{mm})\) hits the target at high velocity and in case of welding copper flyers to aluminum targets, velocity directly and steadily decreases with increasing distance to this edge. Contrary, in case of welding aluminum flyers to copper targets, the velocity remains high in a region of several millimeters (in several cases this region extends up to approx. 5 mm) and often even an increase of the velocity can be observed here, before it drops. This is probably because aluminum flyers are of significantly lower density and mass compared to copper flyers and therefore they can be accelerated easier.

Considering the distribution of the impact angle along the flyer surface, the principle shape of the curves is similar for welding copper flyers to aluminum targets and vice versa. At the flyer edge the impact angle is relatively small and it increases with rising distance \(d\). Frequently, a maximum value is achieved for a parameter-dependent distance and if this value is exceeded, the impact angle quickly decreases again. The fact that in case of welding aluminum flyers to copper targets (example a in Fig. 3) the slope of the curves by trend is smaller is due to the slightly smaller initial gap width between flyer and target in this specific example (for details about this influence compare [12]).

![FIGURE 3. Local distribution of the collision parameters for welding copper flyers to aluminum targets and vice versa](image)

**EXPERIMENTAL IDENTIFICATION OF WELDED AREAS**

All parameter combinations considered in the numerical study were also tested experimentally. In order to guarantee reproducibility of the results, at least three joining experiments were carried out for each parameter combination. It was evaluated whether or not welding of the joining partners occurred.

For all parameter combinations leading to welding, lap shear tests were carried out. Details about these tests can be found in [12]. Welds of specimens failing in the base material during the lap shear test were evaluated as high quality welds, since the strength of the joint is higher compared to that of the base material, here. Relevant sections of these joints were cut, embedded, and polished for micrographical analysis. Various pictures were combined to a panorama view of the complete welded area as exemplarily shown in Fig. 4. These panorama views served for
measuring the width and position of the weld seam. Measured widths varied between 1.54 mm and 3.23 mm for welding of copper flyers to aluminum targets and between 1.89 mm and 5.60 mm for welding of aluminum flyers to copper targets. Typically, the weld seam starts in a short distance to the flyer edge while there is a small gap between flyer and target in the area of the flyer edge. This effect can be attributed to the hobbing motion of the flyer and the according lifting of the flyer edge shown in the process states presented in Fig. 2.

**Process parameters:** capacitor charging energy: $E=30$ kJ; initial gap width: $g=3$ mm;  
Flyer: material: Cu-DHP; thickness $t_{fly}=1$ mm; edge position: $x_{fly}=2$ mm  
Target: material: EN AW-1050; thickness $t_{target}=2$ mm; edge position: $x_{target}=14$ mm

![FIGURE 4. Panorama view of a micrograph indicating the width of the weld seam](image)

**CONSOLIDATION OF NUMERICAL AND EXPERIMENTAL RESULTS**

Finally, the local collision parameters and the positions of the welded zones were correlated to each other in order to provide quantitative collision parameter based process windows. This means, that for numerous points of the flyer surface the local collision parameters are entered in a diagram and different indicators show whether or not welding was achieved for these conditions (compare Fig. 5).

![FIGURE 5. Process window for welding Cu-DHP flyers to EN AW-1050 targets and vice versa](image)

Regions of collision parameters for which achieving high quality welds is most likely and those for which no weld can be expected can be differentiated. However, there is also a transition region in-between these two areas, where the result cannot be predicted safely. For collision parameters in this region no robust welding process can be
expected. Therefore, processes should be designed in such manner that the collision parameters are safely in the high quality zone and not too close to the border of the process window by adjusting a higher impact velocity and/or a smaller impact angle.

CONCLUSIONS AND APPLICATION NOTES FOR USE OF THE PROCESS WINDOWS

A combined numerical and experimental approach was successfully used for quantifying process windows for electromagnetic pulse welding of Cu-DHP and EN AW-1050. For this material combination a minimum impact velocity of approximately 250-300 m/s is required for welding. The collision parameter based process window for welding copper flyers to aluminum targets seems to be similar but not completely identical with that for welding aluminum flyers to copper targets.

In case of welding copper flyers to aluminum targets the window suggests by trend that higher impact angles necessitate higher velocities. However, impact velocities of more than 450 m/s are hardly achievable for copper flyers due to the relatively high density and the accordingly high inertia of this material. Therefore, impact angles of 5°-20° should be aimed at for this process variant. In case of welding aluminum flyers to copper targets higher velocities of up to 650 m/s can be reached relatively easily. Here, angles of up to 40° are possible.

In order to use these collision based process windows for the process design, at first correlations between the adjustable process parameters and the collision parameters have to be determined for each specific setup and equipment that will be used in the process. This can be done either via measurement or via numerical simulation. Then the adjustable process parameters should be set in such manner that the corresponding collision parameters are safely in the zone where high weld quality can be expected.

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REFERENCES