Dissimilar Metal Joining: Macro- and Microscopic Effects of MPW*

Göbel, Gunther[1]; Beyer, Eckard[1,2]; Kaspar, Jörg[1]; Brenner, Berndt[1];

[1] Fraunhofer Institute for Material and Beam Technology (IWS), Dresden, Germany
[2] Institute of Surface and Manufacturing Technology, Technical University Dresden, Germany

Abstract

Magnetic pulse welding (MPW) can offer unique advantages over other joining techniques when applied correctly. Especially for dissimilar metal welding it has several advantages due to its very low heat input and short process times. Due to the high demands of the process on the welding system properties, it is vital to understand the process as detailed as possible to reduce system-related challenges and costs.

The paper discusses similarities and dissimilarities to other high velocity joining processes like explosion welding. Specific aspects of MPW, like its special transient nature are presented and their impact on welding parameters are explained. Using results of example welds on similar and dissimilar metal joints, microscopic and macroscopic effects of part geometry, metallurgical behaviour and pulse parameters are shown.

Concerning microscopic effects, the question is discussed whether interfaces of dissimilar metals can fully be free of intermetallics. This is a relevant question in relation to achievable joint strength, joint ductility and even electric conductivity. Here evidence of recent SEM and TEM analysis is presented. Conclusions are drawn with respect to optimal process conditions and practical geometric relations on the macroscopic scale.

Keywords

Welding, Interface, Analysis

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1 Introduction

Magnetic Pulse Welding insights are a recurring topic for ICHSF contributions due to their relevance for industrial users and the scientific community working on high speed joining techniques. The basic principle will therefore only be addressed very shortly, see Figure 1 for the most common tube compression setup. Here a compression coil is positioned around the two axissymmetric parts. The coil is coupled to a pulse generator usually consisting of a capacitor bank and a high-current switch that generates a strong pulsed magnetic field when loaded and triggered. Due to induction effects, strong currents are generated in the flyer tube. This leads to Lorentz forces in the flyer tube that are usually referred to as “magnetic pressure”. If this pressure is high enough the tube collapses on the inner part. If set up correctly, a moving contact line is created between the flyer tube and the inner part that makes welding possible under certain conditions. This effect is discussed in more detail later. Further information on typical setups and applications can be found in previous ICHSF articles like [1].

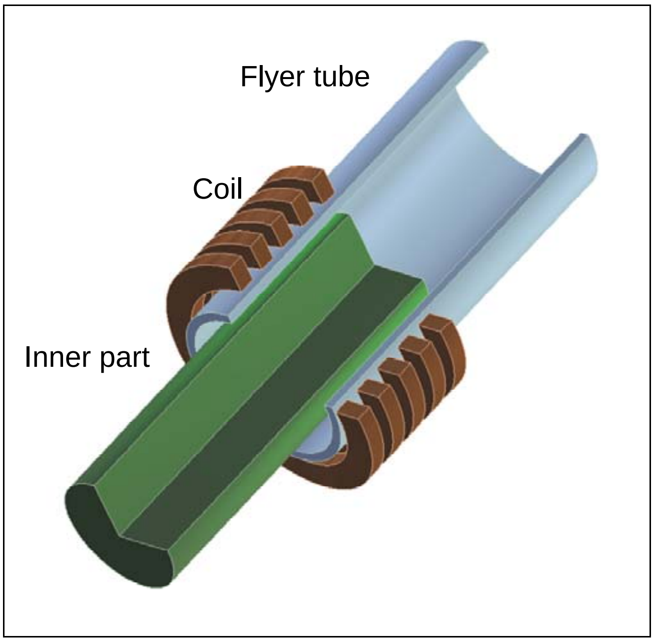

***Figure 1**: principle of MPW, tube compression setup*

In spite of general agreement on the proper setup and behaviour of MPW systems, the physical phenomena during welding are still subject to discussion. Several effects are not clear yet and a consensus has, e.g. for the wavy interface phenomena, not yet been reached. Wave like shaped interfaces are often encountered in MPW welds, see Figure 4 later in this article as an example. As the weld quality is controlled by the interface, the understanding of effects in this region are highly relevant for researchers and end users.

For a better understanding of the underlying effects, experience from other shock welding processes can be taken into account. Especially for explosion welding (EXW) a wide range of literature is available that is dealing mainly with these effects.

In this paper it is discussed whether findings from EXW can be directly applied on MPW or which differences exist. This question is important if further theories like useful parameter windows are derived from existing data.

2 Magnetic Pulse Welding – comparable to other shock welding techniques?

As already discussed in [2] explosion welding (EXW) is usually considered to be a very similar process to magnetic pulse welding as it is also based on a local moving pressure shock effect. On EXW usually a wavy interface is generated between two flat and smooth plates. Here the (still solid!) material obviously has acted like a fluid under the intense pressure at the welding front. Such a wavy interface is seen in MPW too which suggests the same physical background.

Due to its history, explosion welding (EXW) was earlier analysed scientifically than MPW. Especially the wavy interface effect was studied in great detail, leading to several theories of its origin. The main theories are the “Indentation mechanism” [3], “Karman vortex street analogy” [4], “Helmholtz instability mechanism” [5], “stress wave mechanism” [6], and “mechanism of vibration in the plastic state” [7]. A detailed discussion of their background and assumptions would be out of the scope of this paper. Comparisons can already be found in the literature: [7-11] are examples how their perception evolved from 1975 to 2011. According to previous research at the IWS some evidence points to the fact that stress waves play a role: the wave formation could be influenced by changing the thickness of the inner (not the flyer!) part. This influence would be hard to explain using theories based on quasi-fluid flow effects at the interface, as no changes were made here. But it would support the stress wave mechanism theory: As stress waves travel back and forth through the inner part core a feedback into the welding process can be expected even if no other material property was changed.

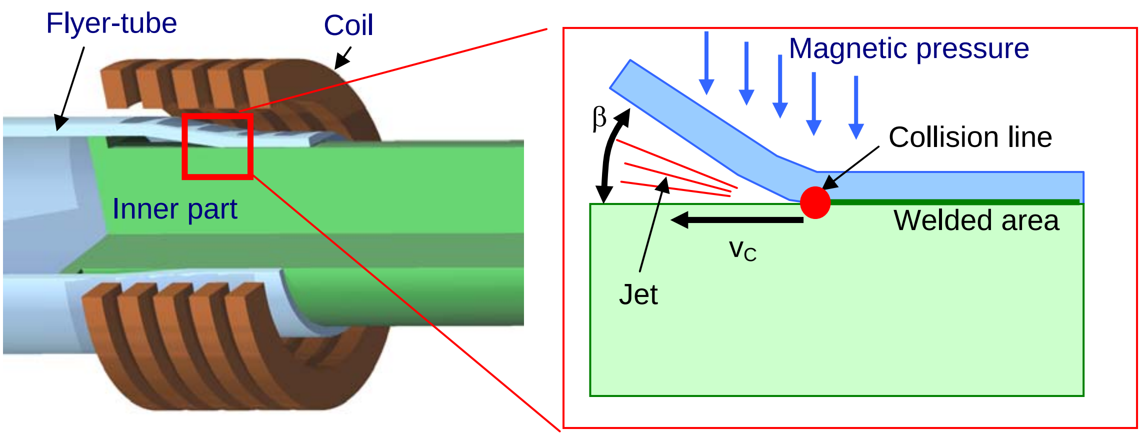

***Figure 2**: jet formation theory*

Consensus of most theories is the presence of a metal-gas jet at the moving welding front, Figure 2. This jet is caused by the intense pressure at the collision point of two surfaces [12]. It is understood that this jet cleans the contaminated and oxidised surfaces directly at the front and makes the welding of the two surfaces possible. It is understood that the jet is only formed in a certain speed range of the moving front. Besides the front velocity v_C other parameters have also been found to be relevant for jet creation, especially the angle β between the two colliding surfaces. A so called "welding window" is formed by v_C and β, see example in Figure 3. In each source [8,14-17] this influence is discussed and different experimental data is contributed.

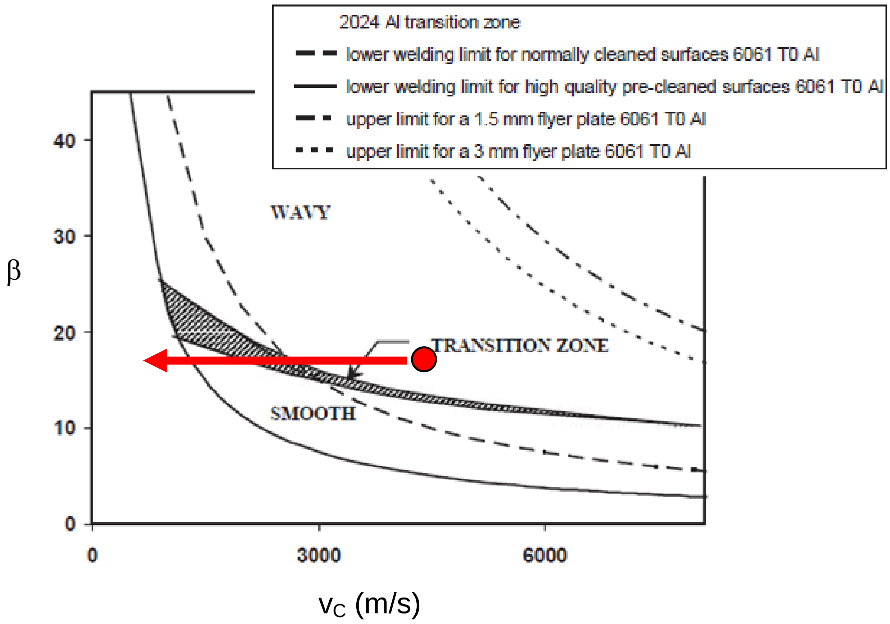

***Figure 3**: Example welding window for explosion welding, governed by velocity v_C and surface angle β from [17], a possible weld path of a MPW process is added (qualitatively)*

Several authors discuss their findings with respect to these process properties which makes a comparison of MPW and EXW results possible. Interestingly, significant differences in the welding windows for a wide range of materials are found. E.g. according to [13, 18, 19] impact velocities for MPW are in the range of v_I=30-250 m/s, while EXW sources point out much higher values in the range of v_I=300-650 m/s [16,20-23]. As the welding window is usually expressed using the resulting front velocities v_C instead of v_I, the mentioned values must be converted using

$$v_C = v_I/\tan \beta$$

As the surface angle β is in the same range for both processes (typical are around 10° for MPW), it becomes clear that the v_C-β welding windows are also set apart by a factor of 2. Recent MPW literature reports relatively high velocities for MPW [24] with v_i up to 320 m/s. Nevertheless these values only reach the lowest end values from EXW.

It could be argued that MPW still follows identical physical effects but operates at a lower parameter range of a generally large window. However, as wavy interfaces are only associated with higher speeds for EXW [12], and waves are commonly encountered in MPW too, further explanations are needed.

As this comparison indicates it is questionable if EXW and MPW physics are really comparable and if EXW parameter windows should be used as a basis for MPW tasks.

However, the formation of wavy interfaces in both processes underlines their general relation. Therefore possible causes are proposed to explain the speed differences.

First it must be pointed out that MPW is, unlike EXW, a highly transient process. The stages of the process are as follows:

1 Acceleration of the flyer part due to the magnetic pulse
2 First contact of the flyer on the fixed part
3 Start of deformation of flyer along fixed part
4 Start of jet, → start of bonding
5 Continuous movement of welding front along part
6 Decay of magnetic pulse (due to higher coil distance as well as end of pulse) → less driving force for deformation
7 End of jet when welding window is left
8 End of deformation

It is clear that a wave formation can, if it happens at all, only take place in stage 5 and 6 during the continuous movement when a jet is present. As the angle of collision can also change due to the deformation behaviour of the flyer, the strong difference to EXW is visible: instead of a constant v_C and β, both parameters change along the weld.

It must be considered that measuring MPW impact speeds or travel speeds is far more complicated than measuring v_C for EXW (where a high-speed recording of the explosion front is sufficient). Therefore it is possible that reduced speeds already occur during stage 6, leading possibly to lower relevant v_C values for MPW.

However, a different explaination can be found in the actual nature of the wavy initiation. Here two different ranges are discussed in the literature: One high speed velocity range, where waves appear also on originally smooth sheets and a lower speed range, which can be achieved by adding disturbances to EXW processes. (Changes to v_C are achieved by influencing the explosive burning velocity via its chemical composition).

These ranges have been proposed earlier by [25] who added wires between the otherwise flat parts during preparation of EXW experiments. The wire was positioned orthogonal to the welding direction and was hit by the moving front during welding. When welding at lower speeds where usually no waves would occur, the wire was able to trigger a wave formation. This leads to the assumption **that metastable wave formation is possible**, if a (strong enough) perturbation exists in the process. This is also in discussion to explain hypervelocity gauging properties. Hypervelocity gauging is another high speed impact process based on fast sliding of two surfaces that causes local welding/ripping features e.g. on rocket sleds or rail guns [10]. A unified theory for both processes can be achieved according to [10] if a metastable instability is considered.

As most EXW information on required speeds for wavy interfaces are based on the overcritical “fully unstable” mechanism on undisturbed flat sheets, it could be concluded that MPW, as a very transient process, should be able to produce waves at much lower front velocities by means of a metastable initiation. Due to the very short total weld length, the initiation is probably already a result of the impact itself in stage 2. Perturbances are expected furthermore due to small symmetry errors (usually caused by not fully symmetric field formers) or by the changing deformation of the flyer along the path.

Besides this different velocity range for wave formation, the welding window position seems to be different for EXW and MPW, as stated from the literature research above. It can be **concluded that a direct transfer of EXW knowledge is not advisable** and differences of the processes should be studied in more detail. Therefore additional research is planned on these discrepancies to find possible explanations.

To increase knowledge of the physical background, it is proposed by the authors that further research on MPW parameter windows should include as many details as possible on the path of the process within the plane of v_C and β. Here pointwise information, as usually seen in literature, is not sufficient to describe MPW processes. By comparing the whole process path in the v_C and β plane, a much better understanding of the influence of different pulse systems, part designs or pulse properties should be possible.

Also the state of contamination was found to be important for the total position of the welding window [17] and should be documented. A thinner contamination layer requires only a weaker jet to clean it. Thus, the lower limit of the welding window is shifted to reduced speeds, making welds possible with less initial pulse energy.

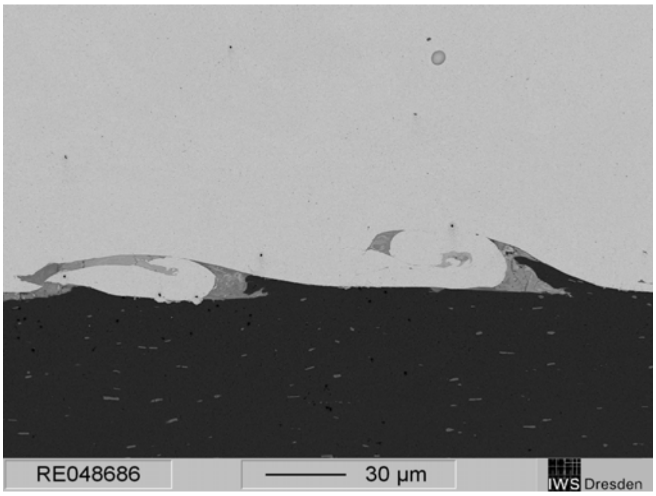

***Figure 4**: typical wave pocket with intermetallics*

Based on theoretical considerations as well as experimental experience the following conclusion can be drawn so far:

- if large impact velocities cannot be reached (e.g. due to pulse generator restrictions), higher angles should be used to stay in the parameter window
- to increase weld length the impact point parameters of a flyer material in a MPW process should be in the far right corner of the v_C-β plane, to be able to use a long path during stage 6 (decay of deformation speed leading to a slowing down of v_C)
- including perturbations in the surface can be used to trigger wave formations
- if strong intermetallics cannot be avoided, (artificially triggered) waves could be used to “localize” oxides in pockets within the waves, see Figure 4
- the surface of the part should be as clean as possible, so already low-energy jets are sufficient to clean the surfaces from all remaining contamination

3 The weld interface – microscopic effects

Special interest has to be paid to the interface itself on a microscopic scale, as its formation controls the properties of the whole joint. The MPW process is often advertised as “intermetallics free” for mixed material joints as it does not need a molten material to join two parts. However, closer inspection usually shows in metallographic analysis and at the latest in SEM analysis that local intermetallics are present, see e.g. [2]. For applications the presence of intermetallics does not automatically mean that the weld is less stable. Here the brittleness of the phases and the size of the phases must exceed certain limits to impair the weld strength. As for many phases, e.g. Al_2Fe_3 for Al+Steel joints or Al_2Cu for Cu+Al joints, this limit is in the range of a few micrometers. This is almost always critical for conventional fusion welding. For solid-state joining methods however, the phase thickness may be significantly lower, depending on the parameters.

The question if a direct transition between neighbouring differing metals is actually possible could not be answered until now. Such a transition would be very interesting, e.g. for electric applications, as electric conductivity is strongly inhibited by intermetallics or oxides. This question was pursued on copper-aluminium joints using TEM images of interfaces created with minimized pulse energies to reduce intermetallics process-wise as much as possible. Pictures and further details of such parts can be found in [2]. Caused by the low energy input, SEM analysis showed strongly reduced presence of intermetallics in comparison to normal MPW joints. Nevertheless pockets of such phases could still be found. Therefore an additional aim of the analysis was to identify the conditions of their formation.

Figure 5a shows a section of the welded zone and Figure 5b-d depict this interface with increasing magnification. The analyzed position was chosen as it included not only sections with no visible intermetallics but also one of the formerly mentioned pockets. Concerning the origin of the latter the following conclusions can be drawn:

- the pocket shows ultra fine grains, which points to a very short temperature peak with subsequent very fast cooling
- the grain orientation is not directional, see SAD (Selected Area Diffraction) image of the region in Figure 5 This is probably caused be equiaxial solidification under strong undercooling conditions
- the whole region shows very small round dots which cannot be grain effects but were identified as ultra small pores → the material seems to have been in a superheated liquid state and was shock-frozen, preserving small gas cavities, an effect known from short pulse laser drilling [26]

After the pocket analysis, all regions with no (SEM-)visible phase seams were examined using TEM. Figure 6 shows a typical region. **A continuous film of additional phases was present throughout all analysed interfaces**. Although the film thickness was often reduced to very low values of 0,05 – 0,2 µm, it never fell below values smaller than 30 nm. A thin region with a film thickness of only 50 - 60 nm is shown in Figure 7.

As it can be seen by the gray-level differences within the interface film, distinct regions exist within the film. According to EDX measurements, the lighter areas consist of a phase with nearly equal atomic percentage of aluminium and copper (probably the η-Phase) while the darker phase is made of nearly 80% copper. This is generally in agreement with findings in larger melt pockets, [2], where also a distinct differentiation of phases is found. A diffusion based bonding mechanism is therefore not likely.

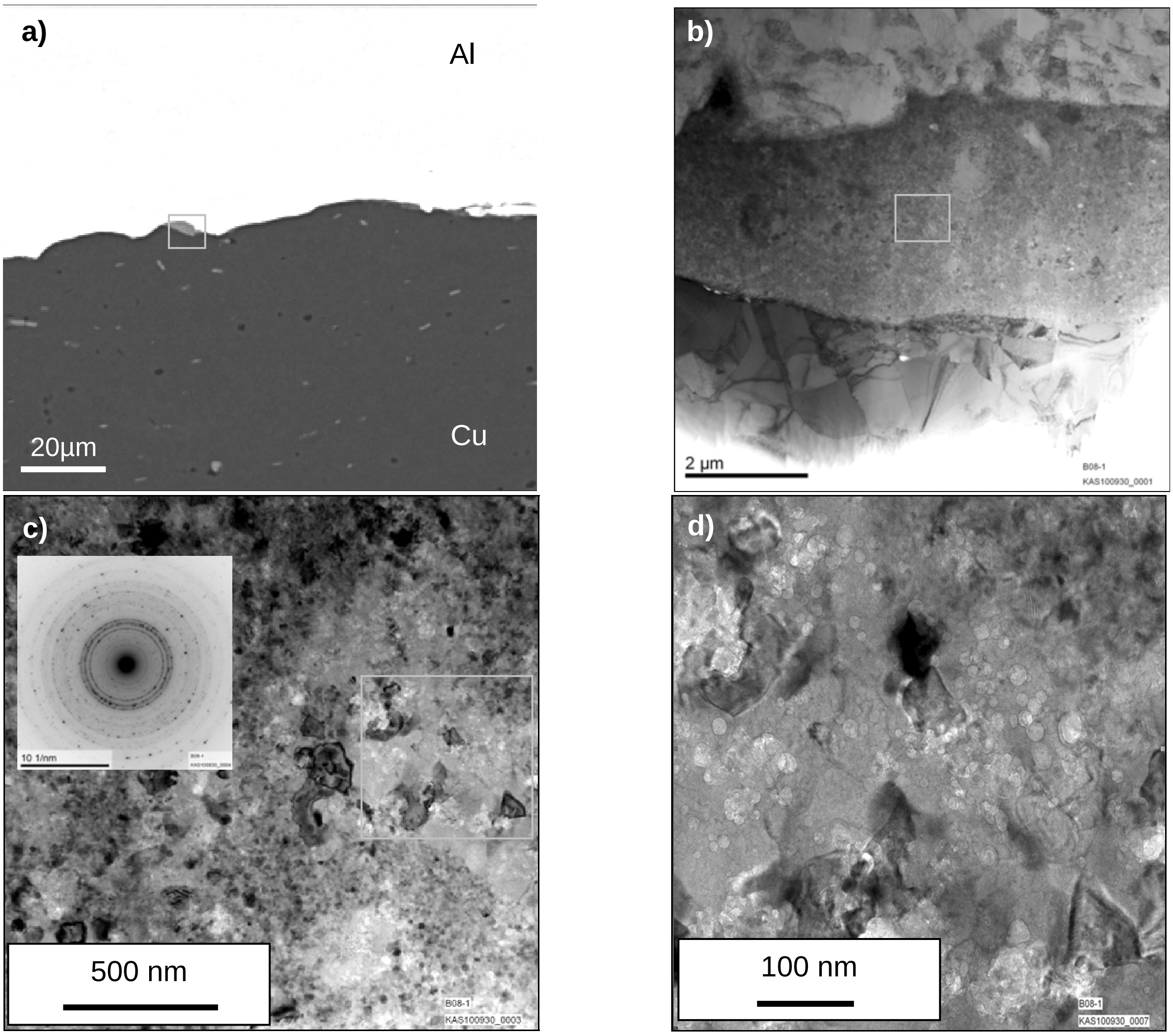

Figure 5 *SEM/TEM images Al+Cu joint with small intermetallic phase pocket, (a): SEM-overview, (b): TEM-Detail phase pocket, (c):grain structure, (d): close up grains*

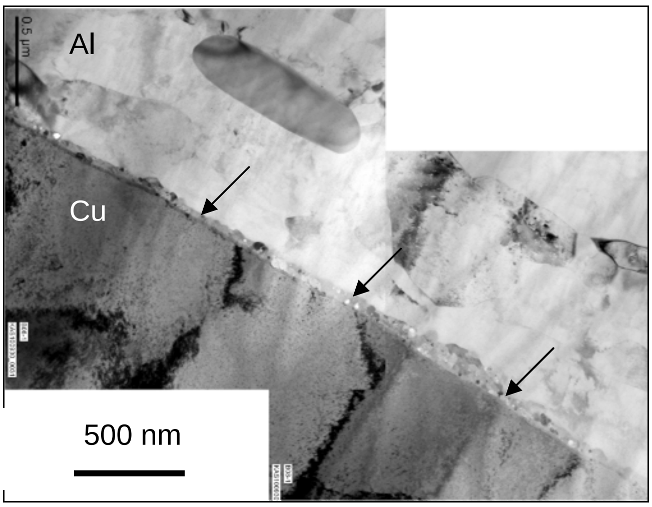

Figure 6*: Continuous intermetallic film (arrows)*

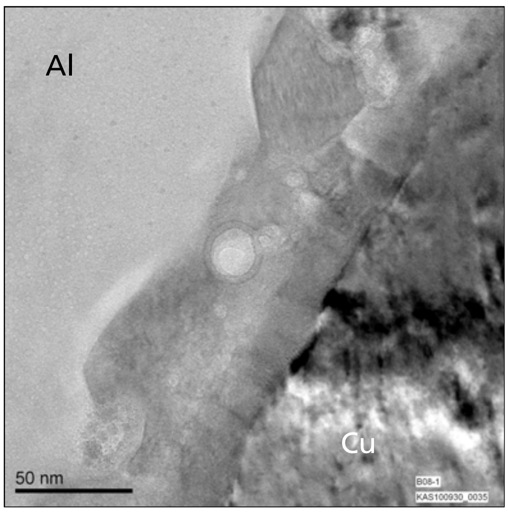

Figure 7*: Ultra-thin interface region*

4 Conclusions

From the theoretical analysis of the process as well as the experimental analysis the following conclusions can be drawn:

- Although generally agreed, the effects and process internals of explosion welding should not be directly transferred to magnetic pulse welding as the parameter windows seems to differ in regard to the collision velocity
- A different wave formation initiation effect is a likely explanation that both EXW and MPW can show wavy interfaces in spite of different welding front velocities
- A metastable wave initiation mechanism is proposed for MPW as this explains the occurrence at lower collision velocities
- As MPW is highly transient in nature and the total weld length extremely short in comparison to EXW, the initial impact or changes and asymmetries along the weld line may already serve as a triggering disturbance for the metastable wave formation
- To enhance the understanding of MPW and to help application oriented research, further studies on the process path in the v_C-β plane should be carried out
- The analysis of low-energy Al+Cu magnetic pulse welds suggests that the idea of an "intermetallics free" joining process cannot be maintained for the MPW process as continuous films were found along all interfaces
- In accordance with previous publications it can be concluded that solid state diffusion is not dominating in the bonding mechanism

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