Insights into intermetallic phases on pulse welded dissimilar metal joints[*]

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Abstract

The Magnetic Pulse Welding (MPW) process has been developed to an industrially used joining method which is considered to be a fast, noncontact, clean and “cold” solid state welding process. Unlike fusion welding, the absence of direct heat during the welding cycle makes it possible to join dissimilar metals, for instance aluminium to copper or copper to steel, without noticeable detrimental metallurgical defects. This is very desirable, as today’s industry lacks technologies to join often not fusion-weldable dissimilar materials effectively. However, current metallographic studies show that for many material combinations the formation of intermetallic seams in the joint region of magnetic pulse welds can not be completely avoided.

Modern technical equipment for MPW is used to join aluminium with copper in order to study the microstructure and the intermetallic phases formed in the weld region in dependence of the processing parameters. The welds are analysed by means of metallographic and electron microscopic (SEM) methods. Relations between the parameters and the microstructures formed within the weld joints are shown. Based on the obtained results conclusions will be drawn with respect to the intermetallic phase formation process and the optimization of the weld microstructure and properties.

Keywords

Welding, Interface, Analysis

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1 Introduction

When joining dissimilar metals with fusion welding techniques, the formation of brittle intermetallic phases is usually considered as the biggest challenge and the primary obstacle to obtain a high-quality weld. To overcome the problem of intermetallic phase formation Magnetic Pulse Welding (MPW), which is generally considered as a “cold” high-speed welding technique, is regarded as an appropriate joining technology.

MPW can be used for applications where a high strength and temperature stable joint is needed. It is not as widely used as Electromagnetic Forming (EMF) due to its higher demands on the electromagnetic equipment.

Like explosion welding (EXW), MPW relies on the dynamic effects when the two joining partners collide at high impact speeds. It is generally agreed that a certain minimal impact velocity v_I and certain collision angle γ is required to start the welding process, and that the partners are welded by a continued movement of the initially joined contact line across the parts. Since the behaviour of the interface during and shortly after the welding front determines the quality of the weld it is regarded as the most important process of MPW and EXW. In order to understand the interface behaviour, to clarify its dependence on process parameters and to optimize the welding process an extensive amount of research has already been conducted by many authors leading to sometimes contradictory conclusions and theories. The present paper is not aimed to review and discuss these theories in detail. Instead, it intents to

- gain information from own experiments and literature about interface behaviour and bonding mechanisms particularly with respect to the formation of wavy structures, intermetallic phases and defects.
- draw conclusions how to set up welding parameters to avoid detrimental effects.

Although the paper deals primarily with MPW, it tries to incorporate the knowledge available from EXW research, if appropriate.

2 Interface effects in shock-welded joints

2.1 Theoretical background

The behaviour and velocity of the moving front in high speed welds has been studied by many authors for EXW and MPW. The materials are bonded by the high transient pressures which are produced by the oblique collision at high velocities. Typical collision point velocities v_C range between 1000 and nearly 4000 m/s. The formation of a so called jet between the surfaces during joining is considered as an important prerequisite for a sound weld, as it strips the surfaces of unwanted surface contamination and oxides and enables them to create a metallurgical bond. Its presence is not in question by most authors and it has even been photographed [1, 2]. However, the reasons for the formation of the wavy interface between the surfaces that follow the jet zone are still in discussion. Prominent theories of the wave formation process are the “Indentation mechanism” [3], the “Karman vortex street analogy” [4], the “Helmholtz instability mechanism” [5], the “stress wave mechanism” [6] and the “mechanism of vibration in the plastic state” [7]. A comprehensive discussion of these theories is e.g. given by Mousavi and Al-Hassani [8]. As an understanding of the interface formation is helpful for the optimization of the weld joint and its properties, essential parts of these theories will be included in the discussion of the results.

2.2 Known detrimental interface effects and relevant parameters

Many researchers have examined metallurgical and geometrical effects along the interface line of EXW and EMP welds and discussed the possible impact on the mechanical behaviour. Relevant elements are: wave and intermetallic phase formation, pockets and films of molten and re-solidified material and inclusions of oxides. Also the formation of cracks, voids and pores, spallation effects, incomplete welding zones, strong plastic deformation as well as recrystallization zones are discussed.

Although many of these effects were analyzed in detail primarily for EXW, they are probably also relevant for MPW. Therefore it is important to know possible relations to the process parameters. Parameters that are often discussed in this regard are:

- Material combination
- Material assignment to flyer/base element
- Thickness of flyer and base material
- Impact velocity v_I
- Collision angle γ (as a function along the weld) [9]
- Collision point velocity v_C (as a function along the weld)
- Pressure (function over time)
- Temperature (e.g. preheating)

As all these parameters must be considered during a process setup, the aim of the following chapters is to examine MPW joints and discuss the findings from experiments and literature with respect to the process setup.

3 Metallographic investigation of weld interfaces

MPW experiments were conducted in cooperation with the High Magnetic Field Laboratory of the “Forschungszentrum Dresden Rossendorf”. The experiments were aimed to create different joint geometries and qualities. They were used as a basis to analyse the already discussed metallurgical and geometrical effects in detail.

3.1 Specimen and methods

A 1.5 millimetre thick Aluminium tube (diameter: 25mm) was electromagnetically joined onto a Copper cylinder with a rim, using different process parameters (Figure 1). Metallographic sections were prepared longitudinal and perpendicular to the cylinder axis. The longitudinal and cross sections were chemically etched, mechanically or ion polished and analyzed by means of optical microscopy, scanning electron microscopy (SEM) and energy dispersive X-ray analysis (EDX). The structural analysis concentrated on the characterization of the structural changes taking place in the welding zone, especially with respect to detrimental effects like cracking or massive intermetallic phase formation.

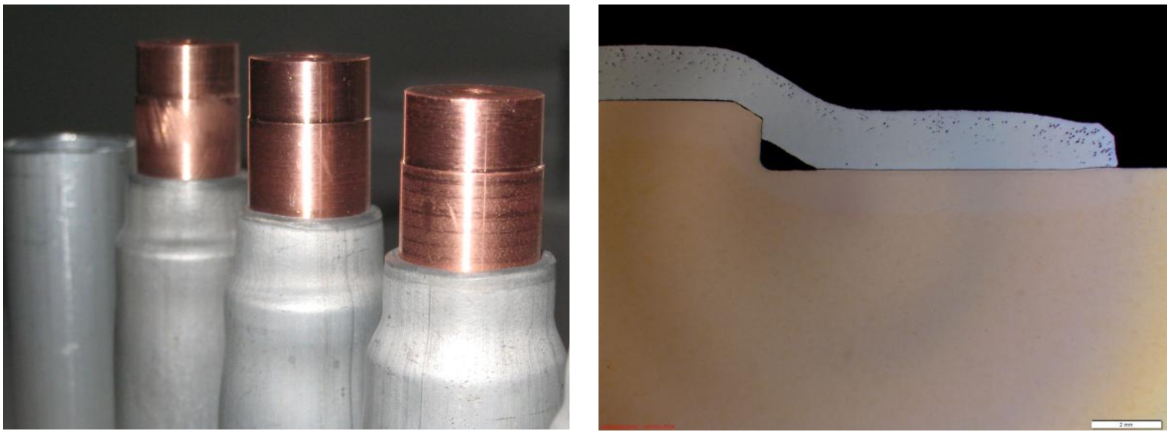

Figure 1: *Test parts made by MPW of a 25 mm diameter aluminium tube onto a copper cylinder, left: welded specimen (and an unwelded tube), right: longitudinal section*

3.2 Experimental Results

Based on the longitudinal and cross sections of different Al-Cu welds the following results, assessments and conclusions should be emphasized:

- The quality of the weld is changing strongly along the interface from start to end for all welds in this configuration. Generally, the start and end zones of the welds exhibited no or only limited bonding. In contrast, the middle section of the welds showed good bonding. The insufficient bonding at the start and the end of the weld zone is a typical feature of MPW cylindrical parts and according to literature not critical for many applications [10, 11]. However, the not connected sections can act as a very strong notch pointing at the weld, which would be very detrimental under cyclic load or corrosive environment.
- The process of wave formation along the interface strongly depends on sample geometry and to a lesser extent also on the process parameters (Figure 2). Using massive copper cylinders and relatively low pulse energies the wave formation was nearly totally inhibited. Contrary, applying hollow copper cylinders and high pulse energies pronounced waves were visible, especially in the middle section of the welds. This geometrical influence is in accordance with findings in [10]. It is important to note that the wave formation process is not mandatory for a good bonding. It is furthermore worth mentioning that to some extent wave formation could also be observed in regions without bonding.
- For the sample geometries and process parameters applied, the formation of intermetallic phases at the welding interface can not be avoided. The composition, arrangement and extent of the intermetallics formed depend on the process parameters chosen and is partly connected with the structure of the interface. If the interface shows a wavy appearance, the intermetallics mainly concentrate in so called “melt pockets”, which are mostly located at the crests of the waves (Figure 3). If EMP produces a waveless interface, the intermetallic phases form a film of varying thickness (Figure 4). It is pointed

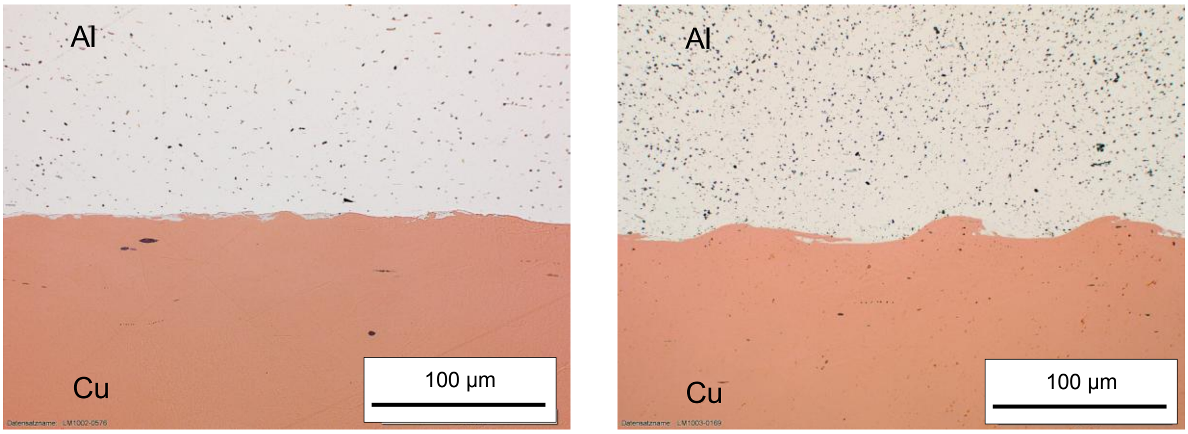

Figure 2: *Cross section details of welds with different interface morphology: (left) nearly waveless interface; (right) wavy interface. Peak pulse current I_{max}=66kA*

out that the phase film appears to be interrupted by regions without any intermetallics. Up to now it is not clear, whether this is true or if the intermetallic film in these regions is too thin to be detected by metallographic methods. For this reason TEM investigations of the weld interface are planned in future work.

- The tendency to intermetallic phase formation rises with increasing pulse energies (Figure 4). For low pulse energies a relatively thin intermetallic phase film is formed. Even if the maximum thickness of the intermetallic film is 5 microns a very good bonding can be achieved. For higher pulse energies the maximum thickness of the intermetallic phase film can increase above 25 microns. Comparing similar bonding conditions, the intermetallic phases are usually thicker if the interface exhibits a wavy appearance.
- The structural and chemical composition of the intermetallics strongly depend on their thickness and hence on the processing parameters chosen (Figure 4 and 5). For a thickness below 5 microns the intermetallics contain rarely any cracks, voids or pores.

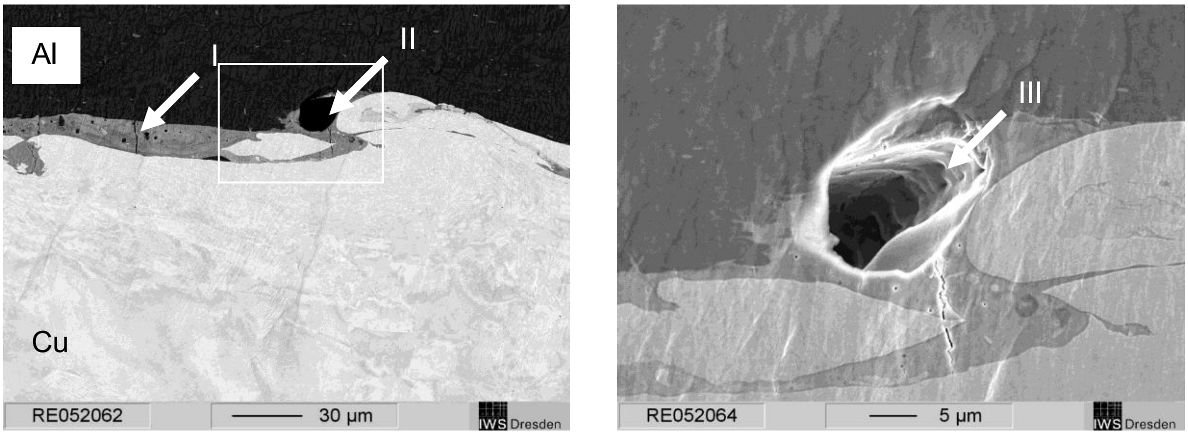

Figure 3*: Details of welds exhibiting typical wavy interface and intermetallics at so called “melt pockets” (SEM micrographs). Left: Note the cracks (I) and voids and pores (II), right: The view into the pore reveals characteristics of a molten and re-solidified surface (III).*

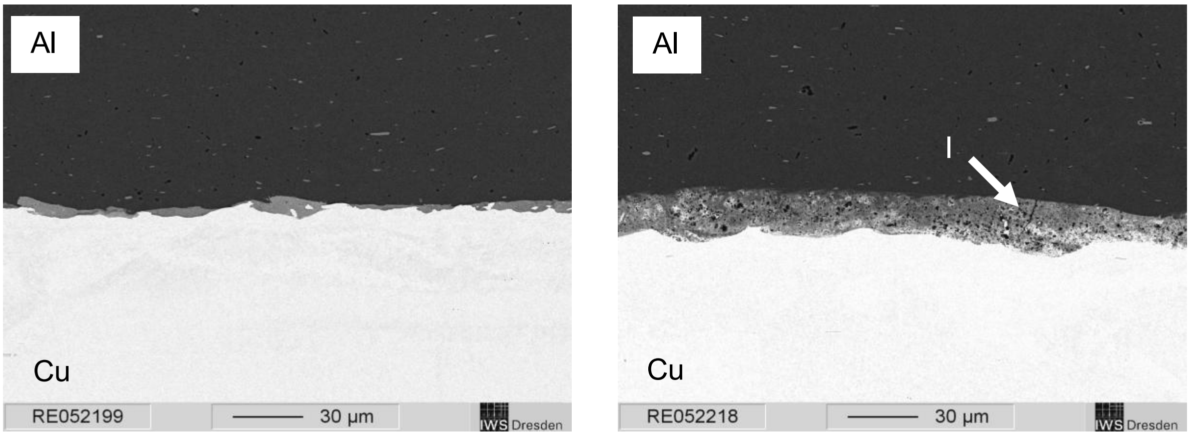

Figure 4: *Details of welds exhibiting waveless interface with intermetallics phase films of different thickness and structural composition (SEM micrographs: z-contrast).*
Left: thin phase film without major defects, I_{max}*=66kA;*
Right: thick phase film containing numerous pores and some cracks (I), I_{max}*=76kA*

- With increasing thickness the intermetallics reveal some voids and cracks running perpendicular to the weld interface. Above a thickness of 10 microns the intermetallics additionally contain numerous pores. Even severe cracking taking place parallel to the weld interface was observed in these samples. EDX analysis (Figure 5) revealed that the thin intermetallic films produced by low energy MPW are generally rich in aluminium containing only between 10 and 20 at.% copper. In contrast, the Cu content of the thicker intermetallics formed during higher pulse energy EMP varies more widely in the range from 10 to 50 at.% copper. Thereby the transition in composition is rather stepwise indicating that different intermetallic phases have formed.
- According to the EDX analysis, the phases identified with SEM cannot be directly linked to the complex phase diagram Al-Cu. Generally only Al-rich phases with a Cu content ≤ 50 at.% have formed. On the Al-rich side of the phase diagram however, only the phases Al_2Cu (θ, 33at.% Cu) and η_2 (50at.% Cu) exist and the Al crystal cannot dissolve significant amounts of Cu under equilibrium conditions. From this it is concluded that the generated Al-rich phases have formed under strong non equilibrium conditions. From the sharp and stepwise transition in chemical composition between the two parent metals and the formed intermetallic phases it is in accordance with Carpenter and Wittman [12] who deduced that solid state diffusion is not involved as active bonding mechanism in the process of MPW aluminium to copper.
- The absence of any diffusion layers leads to the assumption that local melting is mainly involved in the phase formation and bonding process along the interface. As for low pulse energies the intermetallic phases consist primarily of aluminium, it is deduced that solely aluminium but not copper was molten during low energy MPW. In contrast, higher pulse energies which produce thicker intermetallic phase films and so called “melt pockets” enable to exceed the melting temperature of copper locally as well as leading to a higher copper content in the formed intermetallic phases.

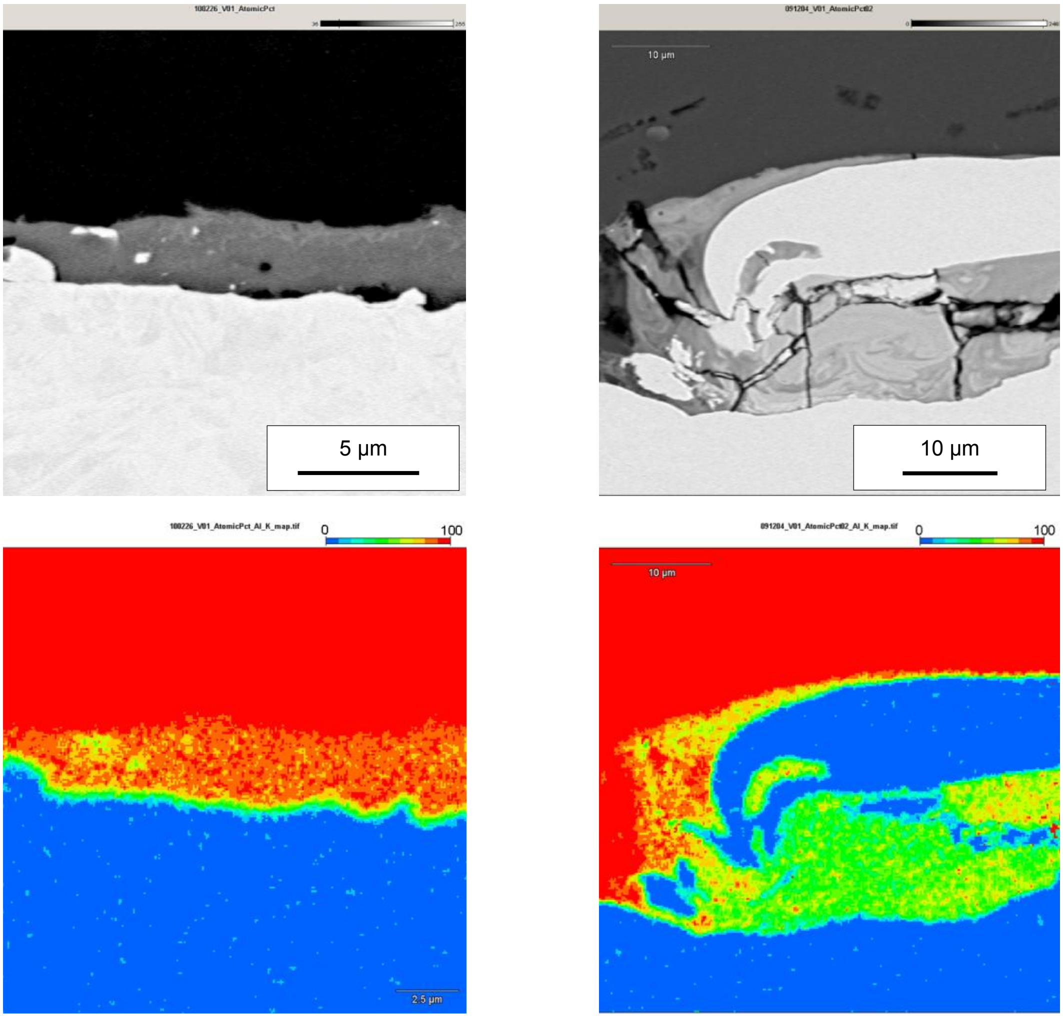

Figure 5*: EDX-analysis of welds exhibiting different Interface morphology (top) SEM micrographs: z-contrast; (bottom) EDX-map: Al content in at.% (left) waveless interface with thin phase film,* I_{max}*=66kA; (right) wavy interface with "melt pockets",* I_{max}*=76kA;*
Note the different magnifications of the images: (left: 5000:1), (right: 2000:1)

- At both sides of the weld, i.e. in the Al- und Cu parent material, a strongly plastically deformed region exists in the vicinity of the interface. On the Al-side the plastic deformation causes an extensive grain elongation in the welding direction. Whereas on the Cu-side the strong plastic deformation leads to dynamic recrystallization resulting in an ultrafine grained structure (Figure 6). Adjacent to the recrystallized zone the copper grains show considerable distortion. The plastically deformed zones on both sides of the weld interface extend to maximum width of 500 microns.
- Although MPW is often discussed as a cold welding process [13, 14] the extreme plasticized regions as well as the common formation of intermetallic phases at the weld interface provide evidence for a localized short-time thermal loading. This can, in principle, lead to similar detrimental effects as in fusion welding, especially when phase films exceed certain thickness limits. Neither the formation of larger melt pockets and thicker intermetallic phase films nor wavy appearances of the weld interface are regarded as prerequisites for high-quality bonds between aluminium and copper. On the contrary,

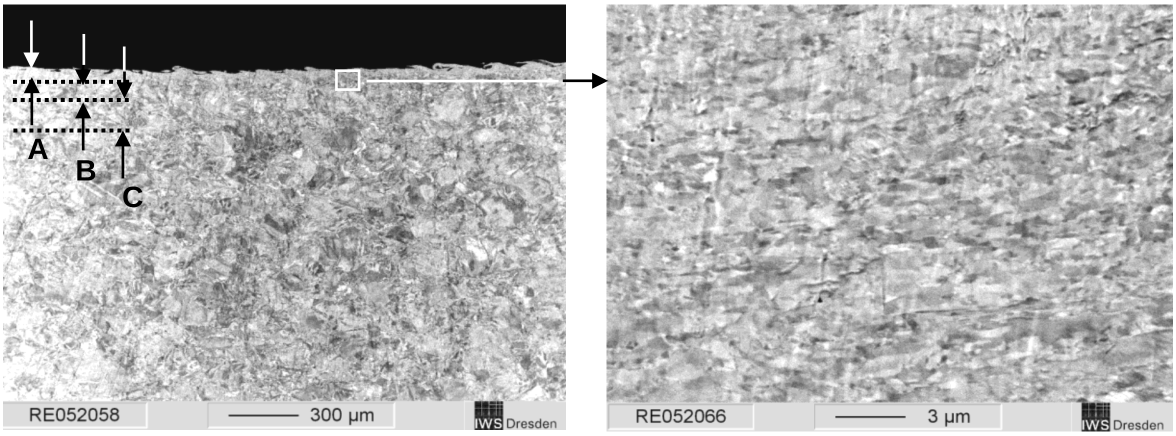

Figure 6: *Details of the structural changes taking place within the Cu adjacent to the weld interface (SEM micrographs: z-contrast). Left: Overview with marked zones; Right: detail of the recrystallized zone,* I_{max}*= 76 kA*
Regions: A = ultrafine recrystallized grains: 20-40µm, B = strongly distorted grains: 30-40µm, C = slightly distorted grains: 200-400µm

the best weld quality is achieved if a very thin intermetallic film, whose thickness does not exceed 5 microns, is formed. Especially in the welds without wavy interfaces perfectly bonded zones exist without any detrimental disturbances and defects.

4 General recommendations

The following conclusions can be drawn from literature and the experiments in regard to an optimal process setup:

- The collision angle is a critical parameter for the initiation of the weld. According to literature, angles between 5° and 20° between the flyer and the base material are regarded as appropriate (e.g. [11, 15]).This is in accordance with our results, where the best welding quality was achieved with a collision angle of approx. 11° at the start of the joint. However it has to be taken into account that, unlike in standard EXW, in typical MPW configurations the collision angle changes continuously from the start to the end of the weld. As a consequence it is difficult to attain uniform weld quality and bonding along the interface. In order to overcome this drawback, future work should try to compensate the unwanted effect by tailoring the geometry of the welding partners or the process parameters [16].
- In order to predict optimum welding conditions for EXW a so called “welding window”, i.e. a plot of appropriate combinations of collision angle and collision point velocity was very successful (e.g. [12, 17]). Although this approach was also suggested for MPW [13], it is unclear if the same concept can be easily assigned and adapted to MPW. Especially the comparability of the processes regarding parameters like pressure, temperature and the variation of these parameters with time are often unknown.
- Literature discussion concerning the importance of wave formation for the weld quality is controversial for both EXW and MPW. Several authors claim that the formation of a wavy interface is compulsory in order to achieve sufficient bonding and high strength welds [12, 14]. This view is not shared by Inal and co-workers [18]. According to these authors, the wavy interface is directly connected with the formation of localized “melt pockets” and thus with harmful intermetallics and cracking. This view is supported by

our results which show that the best weld quality and minimal intermetallic phase formation is obtained if the chosen process parameters result in a straight rather than a wavy interface.

- From literature and our own experiments it is not entirely clear if the formation of intermetallic phase during MPW of aluminium to copper can be completely avoided. We suppose that this is not possible, because localized interfacial melting seems to be a prerequisite for a successful bond. Nonetheless it could be clearly demonstrated that the extent, the structural and chemical composition and the arrangement along the interface can be controlled by the processing parameters. This is of much importance since as soon as the intermetallic phase film exceeds a critical thickness of about 5 microns voids, pores and extensive cracking considerably worsen the weld quality and strength. As seen by the experiments, a reduction of intermetallic phase formation can be directly reached by decreasing the effective impact energy.

5 Conclusion

In the present paper the results of the detailed structural investigations on MPW Al-Cu joints were presented. Based on the results and the conducted literature survey the following conclusions can be drawn:

- The formation of intermetallic phases can not be completely avoided during MPW of aluminium to copper. To confine detrimental effects on the mechanical properties of the joints the thickness of the formed intermetallics should not exceed 5 microns. Above this critical thickness the intermetallics are susceptible to cracking and spallation.
- The variety and chemical composition of the created intermetallics depend on the pulse parameters chosen. This behaviour is attributed to different temperature-time regimes of the process leading to varying amounts of melting of the two base materials.
- Best welding results concerning bond and weld quality can be archived applying relatively low pulse energies. Under these conditions the extent of intermetallic phase formation can be minimized to an uncritical level.
- The formation of a wavy interface is no prerequisite for an effective bonding during MPW

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