Jet Composition in Magnetic Pulse Welding: Al-Al and Al-Mg Couples

MPW jet phenomena were investigated and jet material composition for similar Al alloys and two samples of dissimilar Al-Mg alloy couples were observed

BY A. STERN, O. BECHER, M. NAHMANY, D. ASHKENAZI, AND V. SHRIBMAN

ABSTRACT

Magnetic pulse welding (MPW) produces a mechanically induced essentially solid state but partially fusion-type weld, with an extremely small fusion zone and extremely high cooling rates. Composition of material jet emission in MPW was investigated for similar and dissimilar metal lap joints. The jet residues emitted from Al/Al and Al/Mg lap joints were collected and characterized, and their composition was microanalyzed by scanning electron microscopy with energy-dispersive spectrometry (SEM-EDS). The composition of the jet remains governed by the degree of relative density difference between the two metal components. The metal jet emitted during Al/Mg welding was mainly composed of Mg, the metal component with lower density. The approximate thickness of the layers, peeled during the MPW process, was calculated; an average thickness of 15 μm was found for the Al-Al couple and for Al-Mg couples the values were about 10 μm.

KEYWORDS

- Magnetic Pulse Welding
- Al-Al Couple
- Al-Mg Couple
- Jet Material Composition

Introduction

The principle of magnetic pulse welding (MPW) is briefly summarized below. During the MPW process, the metal parts collide with each other at a high velocity as a result of repulsion between magnetic fields. The magnetic pressure is produced through a rigid coil, while the impulse current is supplied via a capacitor bank. The repulsion between the coil magnetic field and the induced magnetic field on the outer workpiece results in a J × B force (Lorenz force) that causes an oblique collision of the outer workpiece onto the inner part to be welded, at speeds reaching 700 m/s (Refs. 1–9). The collision of the metal couple creates a jet consisting of a mixture of surface contaminants, gases, and hot metal, ejected from the adjacent surfaces of both metals. The two parts of the joint are then forced together to form a solid-state weld, while the whole process takes less than 100 μsec — Fig. 1.

As well established, the collision pressure is proportional to the flyer momentum, which is dependent on the collision velocity. With increasing pulse energy, the traveling velocity of the flyer workpiece increases the collision pressure at the interface and likewise increases. Since the open end of the welded sample is located near the middle of the coil (where the magnetic flux density is maximum), this area is subjected to the maximum magnetic pressure. The acceleration of the outer tube through the standoff gap is higher near the open end of the tube due to higher magnetic pressure and decreases down to zero at the weld end where there is no movement of the outer tube (Refs. 6–8). As a result, the collision is oblique and the initial part of the joint collides at a high collision angle and at very high collision velocity; frequently, no bond is formed in this area. In MPW, just as in explosion welding (EXW), there is a welding window defining the angular impact range in which welding can take place (Refs. 10, 11). As the weld progresses, the outer component is accelerated and collapses under the magnetic pressure; meanwhile, the collision angle decreases and the collision velocity declines gradually to zero. Simultaneously, the local temperature of the materials’ interfaces is increased significantly under the action of the shock waves and the severe plastic deformation (Refs. 2–4).

Many researchers have studied geometrical and metallurgical features along the interfacial zone of EXW and MPW joints and discussed the possible impact on the joint properties. Pertainent elements include wavy interface geometry, pockets and films of molten and resolidified material, and intermetallic phase formation. Also, the spallation effects, formation of cracks and pores, incomplete welding zones, and local plastic deformation are debated (Refs. 1–25). From literature and our own experiments, it is not entirely clear if the formation of inter-

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metallic phase during MPW of dissimilar metal couples can be completely avoided. Nevertheless, it was clearly demonstrated that the geometry, structural, and chemical composition of the interfacial zone is difficult to control by the process parameters. This is of much importance, since as soon as the intermetallic phase film exceeds a critical thickness of about a few microns, voids, pores, and extensive cracking may considerably deteriorate the weld quality.

Few comprehensive reviews were published in referred journals during the last three years discussing the current state-of-the-art of MPW technology (Refs. 1, 11, 24, 26).

Jet Formation

The interfacial bonding layer, created during MPW, generally has a semi-regular wavy morphology and the wavelength is not uniform along the interface. The transition from a planar to a wavy interface appears to be associated with the increase in shear stresses and in local plastic strain. The magnitude of the interfacial wave is considered to reflect the collision pressure at the interface (Ref. 13). However, the reasons for the formation of the wavy interface between the surfaces are still in discussion. The collision pressure in MPW is estimated to be in the range of one GPa. During EXW, much higher pressure is generated, probably several 10s of GPa, and the magnitude of the interfacial waves are likewise larger than those observed in MPW joints. The local pressure must be of sufficient magnitude to exceed the dynamic elastic limit of the material to ensure deformation of the metal surfaces into a jet. Due to the jet formation, a scavenging action occurs between the two mating surfaces. Jetting makes metallurgical bonding possible by causing the breakup of the contaminant surface films and by exposing virgin metal surfaces, which are brought into intimate contact under high pressure. According to Crossland et al. (Ref. 13), during the impact, welding kinetic energy in the jet would be dissipated as heat, causing melt at the interface. On the basis of experimental evidence, it is commonly accepted that jet formation is an important prerequisite for a sound weld in both EXW and MPW.

In Kakizaki et al. research (Ref. 12), several types of lap joints were fabricated by MPW, and the emitted metal jet was collected. The emission behavior of the metal jet and the resultant interface morphology were investigated, and the chemical composition of the metal jet and the interface morphology were compared with simulation results. When the density difference was large, such as Al/Cu and Al/Ni lap joints, the metal jet was mainly composed of the metal component with lower density, Al.

On the other hand, when the density difference was small or zero, such as for Cu/Ni and Al/Al lap joints, the metal jet was composed of both metal components, more or less equally. Metal jets emitted from Al/Cu and Cu/Al lap joints were collected, and they were mainly composed of the metal component with lower density, Al. In the case of Al/Mg and Mg/Al lap joints, metal jet composition changed, depending on the collision conditions. Through observation of the whole simulation process, they
found that most of the jet material originates from the low density material and as the jet symmetry decreases, the higher density material increases its contribution to jetting (Ref. 12). The experimental results were quite well reproduced in these simulations, as shown for jet formation in Al-Mg couples (Ref. 12, Fig. 10, p. 1006).

Aizawa and his colleagues (Refs. 9, 22, 23) directly observed the metal jets emitted from Al/Al thin sheet lap joints, during MP welding. The jets emitted brilliant lights in the air and the length of the perceived lights was 1 to 2 mm. They also showed that the jet created in Al-Fe couples contains mostly Al.

Only a few experimental studies on jet emission during EXW and MPW have been reported in the literature, as described above. A further investigation of the jet nature and composition during the bond formation is important due to its high practical significance (Refs. 11, 24, 26–28). This paper attempts to integrate and analyze the data we produced during the last few years on the jetting remains accumulated during MPW of similar metals, Al-Al couples, and dissimilar metal couples of Al-Mg.

Materials and Experiments

In this research, the jet phenomenon was investigated for similar Al alloys and Al-Mg couples, components with close physical properties. The melting point of pure Al (density 2.69 g/cm³) is 660°C and the melting point of pure Mg (density 1.74 g/cm³) is 650°C.

In all MPW experiments, the flyer component was in a tubular form, while the stationary component was a round bar placed inside the outer tube. The welding was carried out using a single turn CuCr induction coil with a width of 10 mm, mounted around the outer workpiece. The maximum energy load capacity of 20 kJ at 9 kV machine was employed. The welding root opening range applied was between 1 and 1.5 mm for the three weld combinations, while the energy level range was 9 to 15 kJ. Optimum parameters for the samples were initially checked by peel testing and metallographic surveillance of the interface. The magnetic field in the gap between the coil and the welded components peaked at 16 Tesla. Three specimens were cross-sectioned after welding and then examined. The couples included one sample of a similar Al couple, from Al 6082-T6 (Samples 1); one sample of an Al-Mg couple of Al 1050 and Mg AZ31 (Sample 2); and one sample of an Al-Mg couple of Al 4014 and Mg AZ91 (Sample 3). The Al was the outer (flyer) tube in all the Al/Mg couples. The chemical compositions of the outer and inner workpieces (bulk material) are shown in Table 1.

In order to obtain a sound weld in MPW, the outer part should be highly ductile under dynamic stresses; Al and Cu are usually used as flyers. By using an alloy (i.e., Mg) with different mechanical properties, the joint formation and properties can drastically change; the composition of the jet remains may also be different.

The dissimilar couples (Al-Mg) were selected for this research due to the poor weldability of such pairs when using conventional fusion welding.

Table 1 — Chemical Compositions

<table>
<thead>
<tr>
<th>Sample</th>
<th>Alloy</th>
<th>Compositions (wt-%)</th>
<th>Eight Percentage (wt-%)</th>
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<tbody>
<tr>
<td>1</td>
<td>Al 6082-T6</td>
<td>Al 95.2–98.3, Si 0.7–1.3, Fe ≤0.5, Cu ≤0.1, Mn 0.4–1, Mg 0.6–1.2, Cr ≤0.3, Zn ≤0.2, Ti ≤0.1, Other ≤0.2</td>
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<tr>
<td>2</td>
<td>Al 1050, Mg AZ31</td>
<td>99.5% Al, Si 0.3, Fe 0.4, Cu 0.1, Mn 0.6, Mg 0.1, Cr 0.8, Zn 0.2, Ti 0.1, Other ≤0.2</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Al 4014, Mg AZ91</td>
<td>95.4–98.3 Al, Si 0.5, Fe 0.1, Cu 0.1, Mn 0.4, Mg 0.3, Cr 0.6, Zn 0.1, Ti 0.1, Other ≤0.2</td>
<td></td>
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techniques; the formation of large amounts of low ductility intermetallic compounds in the weld metal is detrimental to the joint mechanical properties (Ref. 1). Al alloys were successfully MP welded to Mg alloys and the jetting nature research is important for understanding the bonding process (Refs. 1, 2, 5, 6, 8, 19).

Metallurgical methods were used in order to determine the welding quality, including visual examination (VT), stereoscopic microscopy, light optical microscopy (LM), and scanning electron microscopy (SEM) with energy-dispersive spectrometry (EDS) microanalysis. The metallographic samples (1–3) were sectioned in the longitudinal cross section (L-CS), according to the ASTM-E3 Standard, one from each of the workpieces. Each sample contains two regions (up and down notation), of the welding zone. The samples were mounted; then the surface was ground with silicon-carbide 240–2400-grit papers, followed by polishing with 5 to 0.3-micron alumina pastes and 0.05-micron colloidal silica suspensions.

The VT and stereoscopic microscopy were performed on all samples in order to detect any visible discontinuities and defects in the welding zone. The metallographic samples were examined under a Zeiss Axio Scope A.1 optical microscope (LM). The samples were characterized by SEM and the composition was analyzed by EDS (Philips Micro FA SEM, FEI Quanta 200). Microanalysis by EDS was used to evaluate the local distribution of alloying elements at the joint and its vicinity, as well as the jet composition. Special MPW joint configurations ensured trapping of jet remains created during the process. The jet’s structure and composition were microanalyzed by the SEM/EDS technique.

Results

Initial VT observation performed on all three samples revealed the presence of jet remnants accumulated in nooks, located at the end of the welding zone. For each sample, two regions were observed (up and down locations). All three samples had a relatively high quality welding zone with a typically wavy interface and no heat-affected zone — Fig. 2. The up and down locations showed a similarly shaped defect. The couples are cylindrical in shape and the jet material has a ring shape that extends the entire circumference of the tube joint. Up and down locations are randomly located depending on the sample orientation when it was sectioned.

All samples exhibited permanent plastic deformation of both the outer and inner workpieces (Figs. 2, 5, 7). In the interfacial welded zones, a few discontinuities such as inclusions, pores, and cracks were occasionally observed. Features observed in this work are consistent with those observed in Ref. 29.

Similar Al Alloy

Sample 1 (Al 6082-T6 Couple)

The general location of the upper and lower jets in the metallographic (LM) samples is shown in Fig. 2A, B, respectively. The panoramic metallographic picture of the similar Al alloy couple (sample 1, Al 6082-T6 alloy), shows the L cross-sectional area of the jet’s residue ejected and captured, during welding: one area located at the upper welding zone (Fig. 2C, upper jet), and the other located at the lower welding zone (Fig. 2D, lower jet). In order to estimate the thickness of the layer that the jet peeled off during the MPW process, jet residual cross-sectional area was measured and divided by the length of the welded interface. Since the upper jet’s area was about 375,000 μm² and the length of the welded interface was 11,000 μm, the estimated thickness of the upper layer is about 17 μm. Since the material mostly consists of Mg, one can safely assume that the majority of the 17 microns layer came from the Mg side. Since the lower jet’s area was about 255,000 μm², the estimated thickness of the lower layer is 13 μm. Using the above approximations, we can safely assume that the average layer of metal removed by the jet along both interfaces is less than 20 μm.

SEM observation of jet residue emitted during the process is shown in Fig. 2E and F for the upper jet and the lower case, respectively. The upper jet had a main crack running along the jet...
remains from one side to the other (SEM images, Figs. 2E, 3) created by a local stress concentration in the low ductility residues. The general morphology of the upper jet was of a porous material containing several 50-μm large pores and a huge amount of medium and small pores — between 1 to 20 μm (Fig. 3). The EDS analysis of the upper jet revealed that the jet remains were composed of a mixture of spongy aluminum and aluminum oxide, with an average composition of 91.9–93.5 wt-% Al and 1.6–3.7 wt-% O, as well as the Al 6082 alloying elements Mg, Si, Mn, and some Fe (Fig. 3D, points 1–4). In comparison, the composition of the Al workpiece adjacent to the jet (Fig. 3D, point 5) revealed a composition of 96.7 wt-% Al along with 0.2 wt-% O, and Mg, Si, Mn, and some Fe.

The lower jet also had a main crack running through the jet material (SEM images, Fig. 2F and Fig. 4A–C), but in this case a large oval-shaped hole (about 400 × 800 μm in size) was observed in the central area of the jet residuals. The hole was probably created because a relatively small amount of jet material was captured in this location, and the jet material solidified along the cavity walls, according to the local geometry of the parts. Another (but slight) possibility is that the jet material was captured and filled the cavity, but a portion of the material escaped through a narrow passage present at the end of the weld. A few perpendicular cracks were also observed in the jet material layer attached to the walls. Longitudinal tensile stresses created in the Al workpieces and associated with the components radial reduction during the process, along with material contraction during the solidification phase, probably played a major role in the layer perpendicular cracking (Ref. 19). The morphology of the lower jet was very different from the material observed in Fig. 5C; the uncracked material in Fig. 5C appears denser and contains substantially less porosity. The small triangular-shaped jet material located at the end of the weld appears to be detached from both the Al and Mg cavity walls. This may be the reason that no cracks were found in the material.

Al-Mg Dissimilar Couples, Components with Similar Physical Properties

Sample 2 (Al 1050/Mg AZ31 couple)

Metallographic (LM, SEM) observation of the Al/Mg couple (Sample 2, Al 1050 and Mg AZ91), revealed only one captured jet residual area with two separate jet material leftovers (Fig. 5). The morphology of Sample 2’s material is quite similar to the jet material observed in the Al/Al sample (Figs. 3, 4), e.g., a spongy material containing several 50-μm holes and hundreds of medium and small pores between 1 μm to 20 μm (Fig. 4). The EDS analysis revealed that the lower jet remains were rich in aluminum oxide particles, containing 37.8–82.1 wt-% Al and 4.8–20.9 wt-% O and up to 1.4 wt-% Mg, up to 0.9 wt-% Mn, and between 10.5–40.3 wt-% Si (Fig. 4D, points 1–4). According to the original alloy (Al 6082-T6) bulk composition, the amount of Si should be up to 1.3 wt-%. The local SEM-EDS high silicon composition may have resulted from remains of SiC grinding and colloidal silica polishing particles inside the pores.

The measured composition of the Al workpiece adjacent jet material (Fig. 4C, Point 1–2) was about 97.0 wt-% Al with no presence of oxygen. In addition, the Mg, Si, and Mn present in the alloy was measured along with some iron (about 3.0 wt-% of alloying elements).
The EDS local area analysis (Fig. 5C, area 1) revealed that the jet residue was composed of 69.0 wt-% Mg, 16.7 wt-% Al, and 10.1 wt-% O, as well as 4.2 wt-% Si. EDS local analysis of the jet material (point 1, Fig. 6A) is composed of 77.6 wt-% Mg, 14.0 wt-% Al, and 7.3 wt-% O, as well as 1.1 wt-% Si. The white inclusion embedded in the Mg AZ31 alloy (point 2, Fig. 6A) contains 42.5 wt-% Al, 33.0 wt-% Mn, and 22.5 wt-% Mg, as well as 1.9 wt-% Si, as expected for a Mn-Al alloying elements and inclusions normally found in Mg AZ31 alloys. No attempt was made to determine the Al-Mg compounds in Fig. 6. Based on previous experience with MPW of Al-Mg couples, one may expect metastable intermetallics. The metallographic image and elemental EDS area mapping of Sample 2 (Fig. 6A) indicates that the jet material contains primarily Mg (Fig. 6C) and some oxygen (Fig. 6D). However, the local SEM-EDS relatively high silicon local composition may result from remains of SiC grinding and colloidal silica polishing particles, found inside pores and cracks.

**Sample 3 (Al 4014/Mg AZ91 couple)**

Metallographic observation of the Al/Mg couple revealed the upper jet’s location (Fig. 7). Since at the right side of the couple a passage was open between the parts, the jet material has probably escaped. SEM observation of the upper jet region revealed scattered jet leftovers (Figs. 7, 8) located and attached along the cavity between the walls, with most of the material accumulated at the opening cavity between the Al and Mg parts’ walls.

The jet material attached to the Al wall (Fig. 8A) was heavily cracked and contained some fine porosity. The EDS local area analysis revealed that the composition was 48.2–54.0 wt-% Mg, 40.5–42.7 wt-% Al, and 4.8–5.0 wt-% O, as well as up to 3.4 wt-% Si and 0.7–0.8 wt-% Zn (Fig. 8A, points 1 and 2). The Al 4014 original bulk composition contains less than 0.2 wt-% Zn, and the MgAZ91 original bulk composition contains about 0.8 wt-% Zn. According to the local jet’s composition, it can be seen that the jet next to the Al area contains much more Zinc than the Al bulk material, with Zn composition close to the Mg bulk material. On the other hand, EDS analysis showed that the jet’s local composition, attached to the Mg wall, was 70.0–78.9 wt-% Mg, 17.2–26.3 wt-% Al, and 3.3–3.9 wt-% O (Fig. 8B, points 1–3). For comparison, the composition of the aluminum alloy was 96.8 wt-% Al, 1.0 wt-% Mg, and 2.2 wt-% Si; and the composition of the magnesium alloy near the jet (in 20-μm distance) was 93.2 wt-% Mg, 4.1 wt-% Al, 2.0 wt-% O, and 0.7 wt-% Zn.

The average composition of the accumulated jet material near the narrow opening varied between 53.8–78.5 wt-% Mg, 17.9–43.3 wt-% Al, and 2.9–4.3 wt-% O (Fig. 9, Point 1–6). Whereas the magnesium composition was reduced from 75.4 wt-% Mg (point 1) to 53.8 wt-% Mg (point 6), the aluminum composition was increased from 20.3 wt-% Al (point 1) to 43.3 wt-% Al (point 6), while the oxygen concentration remained quite constant (Fig. 9B). Elemental mapping of Sample 3 showed that the jet material captured in this sample contains mostly magnesium and low quantities of aluminum (Fig. 10, SEM-EDS).

**Discussion**

In this study, MPW jet phenomena were investigated and focused on the observation of jet material composition for similar Al alloys, Al 6082-T6, and two samples of dissimilar Al-Mg alloy couples.

In all the experiments, the acceleration of the outer aluminum component through the opening was higher at the open end of the tube, due to higher magnetic pressure at this area and decreasing down to zero at the weld end where there is no movement of the outer tube (Refs. 2–4). As a result, the collision is oblique and the impact angle was formed. As the weld progresses, the col-
The local pressure created by the impact is of sufficient magnitude to exceed the dynamic elastic limit of the material and ensure severe shear deformation of thin layers of metal at the adjacent interfaces, forming a jet. Jetting makes metallurgical bonding possible by exposing virgin metal surfaces, which are brought into close contact under high pressure. By measuring the jet residue volumes, the approximate thickness of the layers ejected during the welding process was estimated; an average thickness of 15 μm was found for the Al-Al couple, and using the same scheme for Al-Mg couples (Fig. 11), the calculated values were ~10 μm.

The jet material, according to the SEM-EDS analysis, was composed of a mixture of spongy metals and oxides originating from the thin layers of metal ejected from both surfaces during the MPW process. In the similar Al alloys couple, the captured remains were composed of aluminum and aluminum oxide, where the Al composition was identical to the composition of the bulk metal. The Al-Al jet’s material was very porous, most likely as the result of gases trapped during the solidification period at the end of the welding process. The presence of the longitudinal cracks (seen in Figs. 2, 3) originates from the existence of high springback stresses in the low ductility jet residue material. Chemical composition of the upper and lower remains were similar, with a composition of ~90 wt-% Al and ~5 wt-% O for most points, as well as small amounts (~5 wt-%) of Mg, Si, Mn, and Fe (elements that exist in the Al bulk material). Mg, Si, and Mn are alloying elements in the Al 6082-T6 and the Fe is an impurity. According to this composition, it was concluded that the jet’s material was composed of the Al thin layers peeled off from both workpiece surfaces and its oxide formed during the jetting.

The jet material emitted during MPW of the dissimilar Al-Mg couples (Samples 2 and 3, SEM-EDS analysis), was composed of magnesium, aluminum, and oxides created during the process. All these components were mixed at the elevated local temperatures creating the jet material. Remains of the same particular jet were observed as having different compositions in various locations (Fig. 8). Sample 3 jet composition at point 1 was 75.4 wt-% Mg, and the Mg composition at point 6 was only 53.8 wt-% Mg (Fig. 8C, D). The results show that the jet’s composition varies as a function of the local geometry and distance from the welding zone. Kakizaki et al. (Ref. 12) showed that in the case of Al/Mg and Mg/Al joints, metal jet composition changes depending on the local collision conditions. They found that, typically, most of the jet material originates from the low density material and as the jet symmetry decreases, the higher density material increases its contribution to jetting. This behavior may explain the changes in concentrations of the Mg and Al as a function of the local geometry as measured in Sample 3. It is well documented in all Al-Mg micrographs (Figs. 5–10) that the jet material is very porous, occasionally containing a few large holes and large amounts of medium and small pores in the 1–50 μm range. The results of our experiments, conducted under a cylindrical configuration, show that the jet’s composition for Al/Mg couples varies as a function of the local geometry, as described by Kakizaki et al. (Ref. 12) for the planar configuration experiments and simulations. While density likely plays a key role in the fraction of jet material from each material pair, other properties, such as the melting temperature, may also contribute significantly. In our case, the Mg alloys have a slightly lower melting temperature and a lower density; it is safe to assume that both properties can lead to high levels of Mg concentration in the jet material.

Two types of jet residue material were found: cracked (Al/Al, Figs. 2, 3 and Al/Mg, Fig. 10), and uncracked material (Al/Mg, Fig. 5 and Al/Mg, Fig. 8). The structure of the second type was usually different from that of the first one. The uncracked material looks denser and contains significantly less porosity. The triangular-shaped material located at the end of the weld (Fig. 5B) appears to be detached from both the Al and Mg cavity walls. This may be the reason that no cracks were found in this material. In the first stage of jet material solidification, a coherent network does not form and cracks would
not occur. As the dendrites grow and come into contact, a coherent network forms. Further solidification would produce stress, when the material contraction is restrained by the cavity walls. 

Figure 10 demonstrates that the low ductility remains prone to tearing when attached to the cavity walls, and no cracking was observed when the material was detached. 


