Electromagnetic impact welding of Mg to Al sheets

S. D. Kore*, J. Imbert, M. J. Worswick and Y. Zhou

Magnesium (Mg) and aluminium (Al) alloys have been lap welded using an electromagnetic impact welding technique. Metallographic examination of the welds has revealed sound and defect free interfaces. Complete metal continuity has been observed with a characteristic wavy interface. X-ray diffraction analysis has shown no intermetallic phases and suggested that this electromagnetic technique is a solid state welding process. All the shear strength samples welded with discharge energy of 6·7 kJ failed away from weld either in the plastically deformed zone or in the base metal. Optimum discharge energy has been determined as 6·7 kJ based on the shear strength results of the welds.

Keywords: Electromagnetic, Welding, Magnesium, Aluminium

Introduction

Magnesium (Mg) alloys are the lightest of the structural metals and their density is two-thirds that of aluminium (Al). Magnesium alloys are promising structural materials for vehicle fabrication. Aluminium alloys offer high strength, good formability and weight savings. Hence, Al alloys are also being considered for fabrication of vehicles. In order to use Mg and Al alloys together to exploit their properties, development of reliable joints between Mg alloys and Al alloys is required. Thus, the problem of welding Mg and Al alloys must be studied. A variety of attempts to weld these alloys using fusion welding technology have shown no suitable technique because of the level of intermetallic compounds formed in the weld, resulting in unacceptable mechanical properties.[1] Electromagnetic (EM) welding, being a solid state welding technique, is potentially well suited to avoid this problem. Electromagnetic welding is based on the same principles as explosive welding. During a properly designed EM welding process the approach angle and velocity between the parts are sufficient to remove the oxide layer present on the surface of the sheets by jetting. Thus, two atomically clean surfaces are pressed together at very high pressures to obtain complete metallurgical continuity thus forming an electromagnetic weld between the metals in question.

Electromagnetic impact welding is based on Ampere's observation that current carrying conductors, when placed nearby, exert force on each other. If the currents are in opposite directions, the force generated is repulsive. If the currents are in the same direction, an attractive force will be generated.

To produce the current, energy stored in the capacitors, charged through a DC power supply, is discharged through the work coil. When the capacitors discharge, energy is transferred back and forth between the capacitor (where it is stored in electric fields) and the coil (where it is stored in magnetic fields). The current in the coil is taking the form of a damped sinusoidal function. The damped sinusoidal current set up in the work coil produces a transient magnetic field. The metal sheets that are to be welded cut the transient magnetic field and an electromotive force are induced in them. The polarity of this electromotive force is such that the eddy currents induced in the sheets are in the opposite direction of the ones in the coil. The induced currents depend upon the material conductivity. Finally, the work sheets are repelled away from the coil (towards each other) by the Lorentz force F, which is given by

$$F = J \times B \tag{1}$$

where J is current density and B is magnetic flux density.

The Lorentz force is an impulsive force that is applied for a time in the order of tens of microseconds.[2–7] The impact energy and, hence the occurrence of a weld, depends on parameters like the inductance of the circuit, frequency, capacitor energy, voltage, current and stand-off distance between the sheets. The stand-off distance is the distance by which the sheets to be welded are separated from each other. The velocity acquired by the sheets before impact depends upon the energy imputed and the stand-off distance. The kinetic energy achieved by the sheets due to the high velocity is converted into impact energy.

Skin depth is a measure of the distance that an alternating current can penetrate beneath the surface of a conductor. It is defined as[6]

$$\delta = \left(\frac{\rho}{\pi \mu_0 \mu_r f}\right)^{1/2} \tag{2}$$

where ρ is the electrical resistivity of workpiece; μ_0 is the permeability of free space ($=4\pi \times 10^{-7}$); μ_r is the relative permeability and f refers to frequency.

Department of Mechanical and Mechatronics Engineering, University of Waterloo, Ontario N2L3G1, Canada

*Corresponding author, email koresd@engmail.uwaterloo.ca

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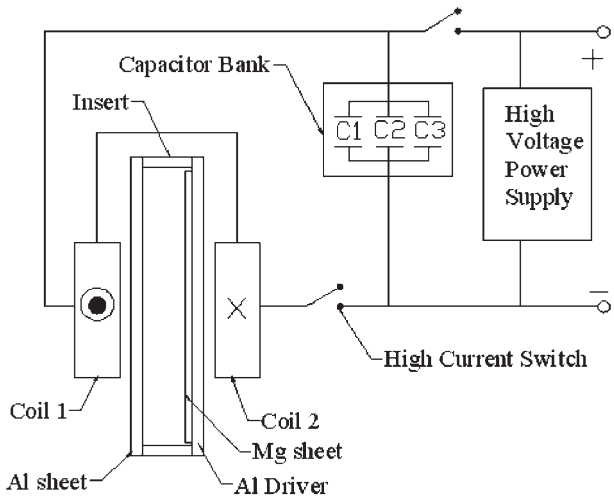


1 Schematic of electromagnetic impact welding setup

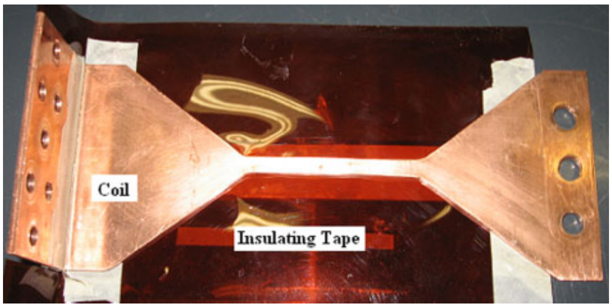
In the case of sheet metal, the skin depth can be greater than the thickness, causing 'leaking' of the magnetic field through the other side, lowering the efficiency of the process. It is desirable for EM welding operations that the value of the frequency should be selected in such a way that the skin depth of the induced currents in the workpiece is less than its thickness. Under this condition an appreciable amount of magnetic field is confined within the thickness of the workpiece and the diffusion of the field beyond it is reduced to a minimum value.

The EM technique has been studied in detail by many researchers for forming and welding of tubes, since in the case of axisymmetric components such as tubes, it is relatively easy to control the magnetic field.[8,9] Researchers have determined that electromagnetic impulse welding has many similarities to explosive welding, such as the critical impact angle, the velocity for joining and a wavy interface after welding.[10–15] The field of EM welding has been also explored for joining similar and dissimilar metal tubes and structural applications.[16–24]

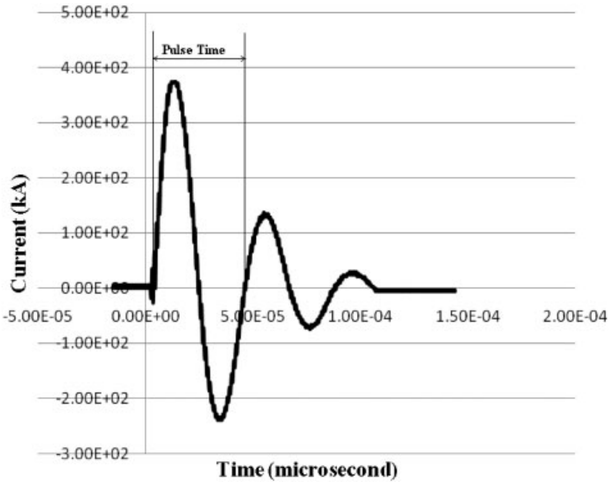
The EM welding technique has, thus far, been mainly studied and applied to tubular structures and has been much less studied for welding of flat sheets, due to the difficulties in designing EM coils and controlling the magnetic fields. Aizawa *et al.*,[2–4] Kore *et al.*[5–7] and Zhang *et al.*[25] have reported the feasibility of EM welding of flat sheets. Kore *et al.*[6,7] have reported a detailed study of effects of process parameters on the strength and width of EM welds of Al-to-Al and Al-to-SS sheets. Published literature showing EM welding of Mg (AZ31) to Al (AA3003) flat sheets has not been found. The objective of the present work is to explore the feasibility of EM welding of Mg to Al sheets.

Experimental setup for EM welding

A Pulsar research edition MPW-20 (Research Edition magnetic pulse generator) was used for the experiments.



2 Electromagnetic welding coil



3 Typical current waveform showing peak current of 369 kA and pulse time of 42 μs (frequency 23·8 kHz) at 6·7 kJ discharge energy

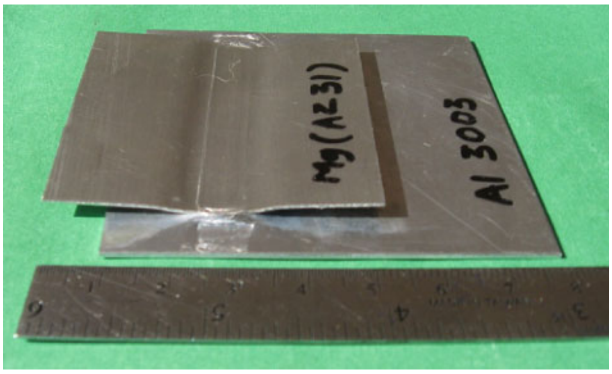
This apparatus consists of a 20 kJ capacitor bank with a 539·7 μF capacitance for energy storage, a high voltage DC power supply, discharge circuit and high voltage switches. The materials used for the experiments were 1 mm thick Al alloy AA3003 sheets cut into 70 mm squares and 0·6 mm thick Mg alloy AZ31 sheets cut into 50 mm squares. The properties of the materials used for the experiments are summarised in Table 1. Henceforth the alloys will simply be referred to as Mg and Al.

A schematic representation of the electromagnetic setup prepared for EM welding of flat sheets is shown in Fig. 1.

The bank capacitance used for all the experiments was kept constant at 539 μF. Two flat dumbbell shaped copper components (Fig. 2) were placed one above another to form a one turn coil. The web of the dumbbell shape was 70 mm long. This shape was used to concentrate the current over the area to be welded. The coil was made from 3 mm thick copper plate and was insulated with Kapton sheet. It was supported with a fixture to avoid bending from the induced forces during welding of the sheets. With the coil and circuit used, the EM welding apparatus had a frequency of ~23·8 kHz.

Table 1 Material properties[26]

Alloy designation and temper	Density, kg m^{-3}	Electrical resistivity, Ω m^{-1}	Yield strength, MPa	Ultimate tensile strength, MPa
Al 3003-H14	2730	4·16 E-8	145	158
AZ31-H24	1770	9·20 E-8	220	270



4 **Typical EM weld of Mg to Al sheets**

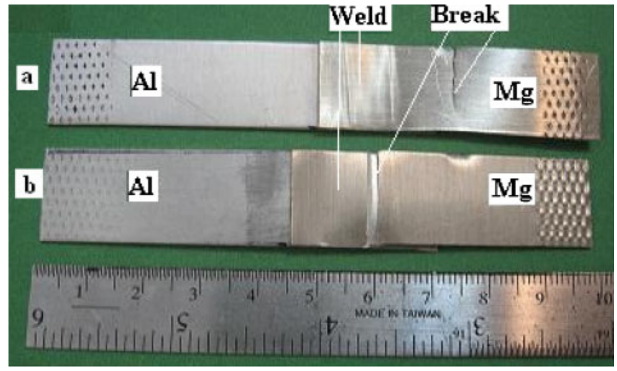
Results and discussion

The relatively poor electrical conductivity of the Mg alloy led to a skin depth of 1 mm with the available frequency (23·8 kHz), which was more than its thickness (0·6 mm) and hence the field was not fully contained, lowering the impact force. Hence, it was not possible to drive Mg sheet by electromagnetic force due to an inappropriate frequency value. Since Al's electrical conductivity is higher, its skin depth at the experimental frequency condition was 0·7 mm. Thus, frequency and skin depth conditions were appropriate for 1 mm thick Al sheets. It was decided to use 1 mm thick Al driver sheets to accelerate the 0·6 mm Mg sheets. Each 50 mm square sheet of Mg was backed up with a 70 mm square Al driver sheet. The Mg sheet was insulated from the Al driver sheet to avoid sparking between them. The prepared samples were placed within the copper coil. Energies of 4·3–9·7 kJ were discharged from the capacitor bank. The current waveform obtained at 6·7 kJ discharge energy is shown in Fig. 3. A sample of Mg to Al sheet welded by EM welding technique is shown in Fig. 4.

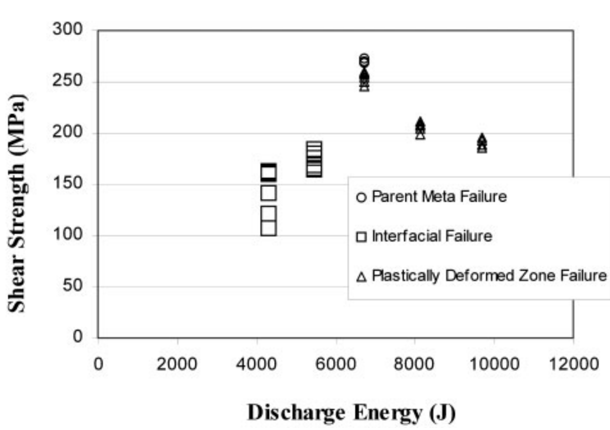
Mechanical and metallurgical testing of welds

Welded samples were cut across the weld and tested for shear strength with a uniaxial tensile testing machine. While conducting shear testing it is difficult to completely eliminate bending stress. Spacers of matching thickness to the Al and AZ31 sheets were used to grip AZ31 and Al sheets respectively to minimise the bending during the tensile shear test. Figure 5 shows the variation in shear strength of the welds with respect to the discharge energy used, for a constant standoff distance of 2·5 mm. With the experimental conditions described above, the minimum discharge energy required for EM welding of Mg to Al sheets was 4·3 kJ. Samples welded with discharge energies of 4·3 and 5·5 kJ showed interfacial failure, with shear strengths less than 180 MPa. A discharge energy of 6·7 kJ improved the shear strength to more than 185 MPa and produced samples that exhibited two types of failures, as shown in Fig. 6. All the shear strength samples welded with discharge energy of 6·7 kJ failed away from weld either in the plastically deformed zone or in the base metal. Some of the samples welded at 6·7 kJ discharge energy failed in the base metal showing that the strength of the EM weld was higher than that of the base metal. At higher energy values such as 8 and 9·6 kJ the plastic deformation of the Mg sheets was severe and failure occurred away from the weld in the severely plastically deformed zone. Thus, based on the shear strength results, 6·7 kJ discharge energy was found to be optimum for the current set of experimental conditions.

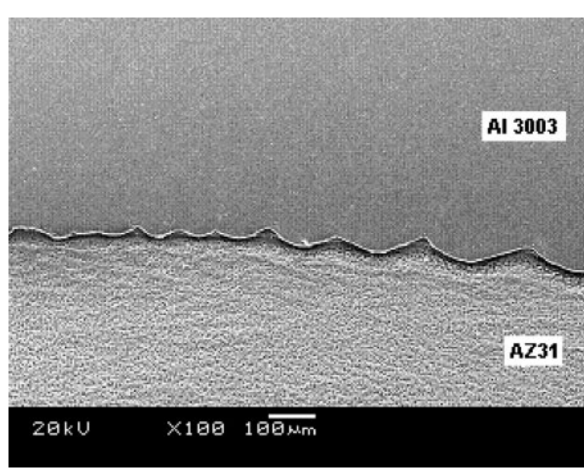
The welded samples were cut across the weld, polished and observed under the microscope to analyse the weld interface. Compressed grains were observed at the weld interface. An SEM image of the weld interface is shown in Fig. 7. The image shows a wavy interface and complete metal continuity without any defect in the weld. No eutectic microstructure has been observed at the interface which indicates that any rise in temperature



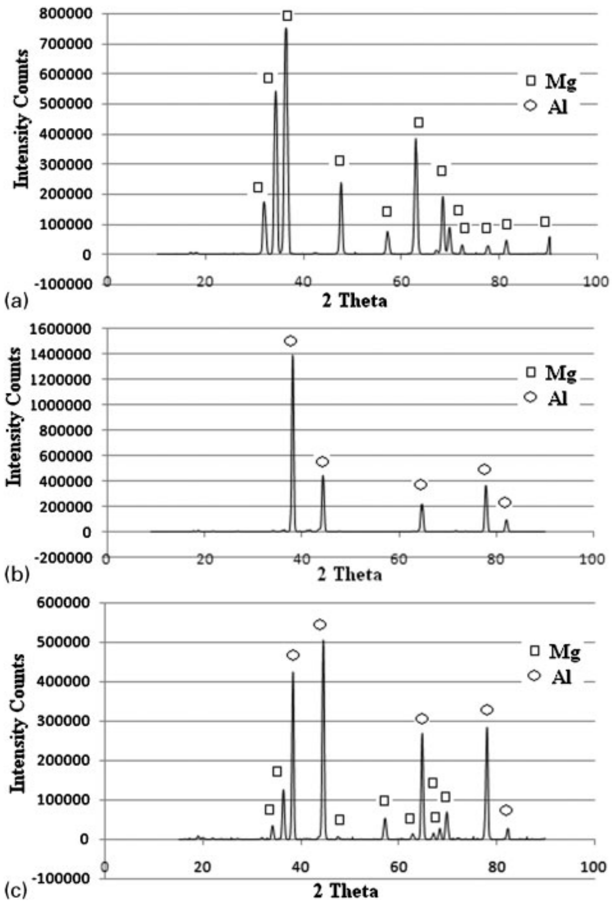
6 **Shear tested samples of Mg to Al welds with failure in *a* base metal and *b* plastically deformed zone**



5 **Shear strength of EM welds with variation in discharge energy**



7 **Image (SEM) of Mg to Al weld cross-section showing wavy interface and complete metal continuity**



8 X-ray diffraction spectra of Mg to Al weld at *a* opened weld interface Mg side, *b* opened weld interface Al side and *c* Al–Mg weld cross-section

during the EM welding process is insufficient to cause melting. The wavy interface that has been observed in these welds is due to the high velocity of impact between the two sheets. This phenomenon is similar to the one observed in the well known explosive welding process.[27]

Rigaku AFC-8 X-ray diffraction (XRD) apparatus, working under 50 V, 40 mA, with diameter of collimator 0·8 mm was used for the XRD analysis. The target was Cu and the wavelength of the X-ray was 0·1542 nm. Cross-section from the weld specimen 7 mm long and 1·6 mm wide was polished to analyse the weld interface. The diffraction was taken from the polished surface of weld cross-section. Samples at lower energy values showed interfacial failure in tensile testing. Those samples are used for XRD analysis across the opened weld interface on Mg and Al side.

The representative results from XRD, which are presented in Fig. 8, indicate that both the Al phase and the Mg phase emitted the strongest signals. These measurements could either suggest that the interfacial microstructure of these EM welds had no intermetallic phases, or that any intermetallic phase must have been exceptionally fine, thus undetectable by XRD technique used in this case. Therefore, the authors assume that there is no melting and formation of intermetallic phases at the weld interface, for the welds formed using the experimental conditions and material combinations studied.

Summary

Electromagnetic welding, being a solid state welding process, has been found suitable for welding magnesium AZ31 to aluminium AA3003 sheets. Owing to the skin depth produced by the frequency of the experimental apparatus and the electrical conductivity of Mg, it was necessary to use Al driver sheet to accelerate the Mg alloy sheet. For the experimental conditions presented, the minimum discharge energy required for the EM welding of AZ31 to AA3003 sheet was found to be 4·3 kJ. All the samples welded at discharge energies more than 6·7 kJ failed away from weld. Samples welded at lower discharge energies (4·3 and 5·5 kJ) exhibited interfacial failure. Discharge energy of 6·7 kJ was found to be optimum, with some of the samples welded at this energy failing in the base metal. Further increase in energy resulted in severe plastic deformation and failure away from the weld in the plastically deformed zone.

The microstructures of the EM welds showed complete metal continuity without any weld defects and a wavy interface, which are consistent with impact welding. No eutectic microstructure was found in the SEM analysis. This suggests that for the current experimental conditions there is no melting at the interface. This indicates that EM welding is a solid state welding process. The XRD measurements could either suggest that the interfacial microstructure of these EM welds had no intermetallic phases, or that any intermetallic phase must have been exceptionally fine, thus undetectable by XRD technique used in this case.

Further research will be carried out to investigate the effect of process parameters such as standoff distance, discharge energy and frequency conditions on strength and metallographic characteristics of Mg to Al EM welds.

Acknowledgements

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