Journal of Manufacturing Processes 19 (2015) 14–21

Contents lists available at ScienceDirect

Journal of Manufacturing Processes

journal homepage: www.elsevier.com/locate/manpro

Technical Paper

# Microstructure evolution during magnetic pulse welding of dissimilar aluminium and magnesium alloys

Shujun Chen, Xiaoqing Jiang*,[1]

*Welding Research Institute, Beijing University of Technology, Beijing 100124, People's Republic of China*

ARTICLE INFO

*Article history:*
Received 17 January 2015
Received in revised form 30 March 2015
Accepted 5 April 2015
Available online 21 April 2015

*Keywords:*
Magnetic pulse welding
Dissimilar aluminium and magnesium alloys
Microstructure evolution
Dynamic recrystallization
Twinning

ABSTRACT

Microstructure evolution has been investigated for magnetic pulse welding of dissimilar aluminium and magnesium alloys using optical microscopy, laser confocal microscopy and electron backscatter diffraction. The welded joints were made with discharge voltages of 4 kV, 4.5 kV and 5 kV and they are characterised by the aluminium region, the weld interface and the magnesium region. The interfacial waves become more regular and much smoother with increasing discharge voltage from 4 kV to 5 kV. The grains were extremely refined and the grain size became larger with increasing distance to the weld interface at a discharge voltage of 5 kV. The gradual grain refinement closer to the weld interface can be attributed to dynamic recrystallization. Different recrystallization behaviour was observed for the aluminium region and the magnesium region near the weld interface. The occurrence of the extension twinning $\{10\bar{1}2\}$ in the dynamic recrystallized grains indicating twin related dynamic recrystallization behaviour in the magnesium region near the weld interface.



## 1. Introduction

Magnetic pulse welding (MPW) is a welding process that uses magnetic forces to weld two workpieces together. The welding mechanism is most similar to that of explosion welding [1]. MPW uses electromagnetic force to generate high speed collision between the metal pieces leading to atomic bonds. MPW is based on the concept of discharging a high energy current through a coil surrounding the workpiece during a very short period of time. Fig. 1 shows the schematic layout of the magnetic pulse system [2], where an intense magnetic field is locally produced to generate a secondary eddy current in the flyer according to Lorenz's law. The high and extremely fast current creates magnetic forces (Lorentz force) between the coil and the outer work piece that causes the joining of the outer and inner work pieces and a solid state cold weld is then formed [3]. MPW is a solid-state joining process that can be used to weld dissimilar metal joints, such as aluminium to brass, copper to steel, titanium to stainless steel, aluminium to copper and aluminium to magnesium, etc. [4]. It has many advantages, firstly, it does not require the direct contact of tool and workpieces and the MPW machines can produce high accuracy and good surface finish. No protecting atmosphere, filler materials or other aiding materials are necessary. Secondly, it does not require periodic adjustments as is common with conventional machining; no heat affected zone is created. Finally, the MPW process lasts no longer than 100 μs, thus, it has cost efficiency [2,5,6].

Weight reduction is one of the major means available to reduce the production costs of automotive and aerospace industry. Low density aluminium, magnesium and its alloys are beneficial for weight reductions. And the use of high quality dissimilar joints of magnesium and aluminium alloys has been applied to automotive and aerospace industry [5,6]. MPW is one welding method for joining dissimilar magnesium and aluminium alloys.

MPW has been intensively studied in the literature in terms of microstructure of the weld interface of dissimilar aluminium–magnesium alloys and similar magnesium–magnesium alloys [4,7–14]. Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) were used to study grain refinement and plastic deformation behaviour of the materials adjacent to the weld interface of similar magnesium–magnesium alloys [13,14]. The weld zones of MPW are classified as unbonded zone and bonded zone [10]. The bonded zone used in this work is defined as the welded joint characterised by the magnesium region, the weld interface and the aluminium region. Interfacial waves were formed in the weld interface with high levels of discharge voltage and the weld interface morphology of magnetic pulse welded magnesium–aluminium has been investigated by Refs. [9–12].

* Corresponding author. Tel.: +86 10 67392521; fax: +86 10 67392521.
*E-mail addresses:* sjchen@bjut.edu.cn (S. Chen), xqj225@hotmail.com, xjiang@bjut.edu.cn (X. Jiang).
[1] X. Jiang, formerly PhD Student with the Department of Materials Science and Engineering, The University of Sheffield, UK.

http://dx.doi.org/10.1016/j.jmapro.2015.04.001

**Table 1**
Chemical composition of the base material, in wt%.

| Material | Al | Si | Ca | Zn | Mn | Be | Fe | Cu | Ti | V | Mg |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1060 Al | 99.6 | 0. 25 | – | 0.05 | 0.03 | – | 0.35 | 0.05 | 0.03 | 0.05 | 0.03 |
| AZ31B Mg | 3.19 | 0.02 | 0.04 | 0.81 | 0.334 | 0.1 | 0.005 | 0.05 | – | – | 95.45 |

Aizenshtein et al. [10] reported that the MPW process produces a mechanically induced local fusion type weld, with an extremely small fusion zone and no heat affected zone. The bonded zone displays a discontinuous pocket type or a continuous microscopic interface layer along the interface. Moreover, Stern et al. [11] found that the weld interface layer has a typical wavy pattern with an average thickness of 20 mm. The interface layer is practically uniform due to the local melting effect, intensive mixing of the melt and a rapid rate of solidification intermetallic β phase $Mg_{17}Al_{12}$. Moreover, energy dispersive X-ray spectroscopy (EDS) line scan results by Chen et al. [12] showed that the intermetallic compounds were $Al_3Mg_2$ and $Al_{12}Mg_{17}$ in the weld interface. However, an X-ray diffraction analysis by Kore et al. [9] showed that no intermetallic phases were formed in the weld interface. The common feature of the weld interface region created during the MPW process is the increase of hardness in the weld interface. The increase in hardness is the result of intermetallic phase formation and the fine-grained microstructure [11]. The formation mechanism of interfacial waves in magnetic pulse welding is similar to that of impact welding, while the wave formation mechanism of impact welding includes: indentation [15], vortex street [16], stress wave [17] plastic deformation [18] and Helmholtz instability [19]. Helmholtz instability occurs where shock waves propagate through the metal parts during the explosive welding process, leading to periodic interference perturbation at the weld interface. The interfacial waves are then formed due to discontinuities of the flow velocity difference between the outer workpiece and the inner workpiece in MPW process [8,19–22]. In indentation mechanism, the parent plate deforms under the stagnation point and consequently a hump is formed in the parent plate ahead of the point of collision. The hump builds up and eventually traps the re-entrant jet. The stagnation point then transfers to the top of the hump, descends and then starts forming a new hump, and in this manner successive waves are formed in the interface [15]. In vortex street mechanism, wave formation of the bond zone during explosion cladding is analogous to the formation of vortex streets in fluid flow around an obstacle or in the collision of liquid streams and the wave is caused by plastic flow stresses [17].

This work aims to characterise the microstructure and recrystallization behaviour of the materials near the weld interface of the MPW joints of dissimilar aluminium and magnesium alloys.

## 2. Experimental methods

The as-received base material was as-annealed 1060 aluminium and as-rolled AZ31B magnesium. Chemical composition of the base material is shown in Table 1. MPW of 1060 aluminium and AZ31B magnesium were carried out on a Pulsar 20-9 machine and the experimental conditions are shown in Table 2. Welded sample surface was washed by acetone and the oxide layers and contaminations on the surface were removed before the MPW test. Three aluminium–magnesium welds were made at discharge voltages of 4 kV, 4.5 kV and 5 kV, respectively. Fig. 2 shows the design for the inductive coil and the field shaper. The inductive coil has 4.5 turns and the field shaper to focus the magnetic field has a work zone of 10 mm length with a radial gap of 1.5 mm. The outer tube was annealed 1060 aluminium with a diameter of 16 mm, thickness of 1 mm and length of 34 mm and the AZ31B magnesium inner solid cylinder consists of two parts with a total length of 38 mm. One part has a diameter of 11 mm and a length of 15 mm and the other part has a diameter of 12 mm with 23 mm length.

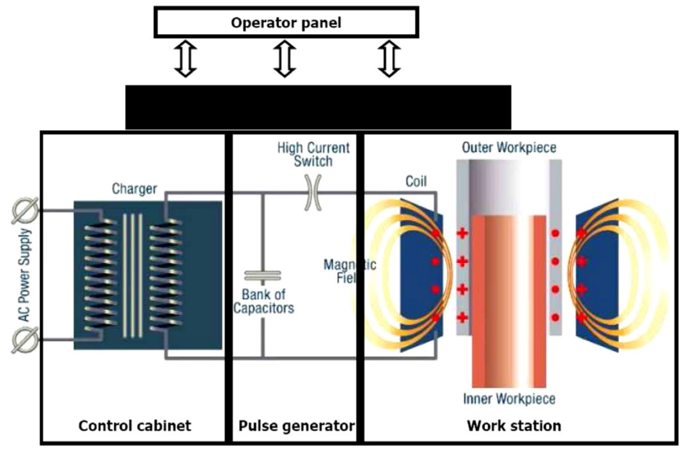


**Fig. 1.** Schematic magnetic pulse system layout [2].

**Table 2**
Experimental conditions of the MPW tests.

| Contents | Description |
|---|---|
| The maximum energy storage | 20 kJ at 8.5 kV |
| Welding energy (continuous operation) | 13.5 kJ at 7 kV |
| The maximum discharge current | 600 kA |
| Welding current | 400 kA |
| The maximum voltage | 8.5 kV |
| Charging time | 1.75 kJ $s^{-1}$ |
| Capacity | 552 μF |
| Inductance | 30 nH ± 10% |
| Short circuit current rise time | 10 μs |

Specimens for microstructure analysis were prepared for cutting, grinding and polishing using standard procedures. The progressively finer grades of silicon carbide grinding paper at 800 grit, 1200 grit and 2000 grit were used for grinding [23]. After grinding, initial polishing was carried out for 10 s with 5 μm, 2.5 μm, 1 μm diamond paste until a satisfactory polish was achieved. Final polishing was carried out for 2 min using a polishing cloth with a solution of 0.05 μm colloidal silica suspension. The etchant used for AZ31B magnesium alloy is acetic picral solution (5 ml acetic acid, 6 g picric acid, 10 ml distilled water and 100 ml ethanol). The sample was immersed in the etchant for 15–20 s. The etched sample was washed in running distilled water and thoroughly dried before microscopic characterisation [24]. Microstructure analysis was performed by Shanghai 4XC-1 optical microscopy, Olympus Lext confocal laser scanning microscopy. For EBSD analysis, the magnesium base material after the 0.05 μm colloidal silica stage was electropolished for 30 s using a solution of 25% nitric acid in methanol at a voltage of 10 V and at temperature of −20 °C to ensure a strain-free surface, stainless steel is used as a cathode for the electro-polishing process. The base material 1060 aluminium was electropolished with a solution of 30% nitric acid in methanol for 60 s at approximately −14 °C with a voltage of 12 V. EBSD was carried out using a scanning electron microscope equipped with a fully automatic TSL Genesis 7000 EBSD attachment. Data processing was then carried out using HKL Channel 5 software and TSL OIM software.