Materials and Design 62 (2014) 344–351

Contents lists available at ScienceDirect

Materials and Design

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

Ultrasonic spot welding of Al/Mg/Al tri-layered clad sheets

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ARTICLE INFO

Article history:
Received 23 January 2014
Accepted 8 May 2014
Available online 27 May 2014

Keywords:
Magnesium alloy
Clad sheet
Ultrasonic spot welding
Lap shear strength
Hardness

ABSTRACT

Solid-state ultrasonic spot welding (USW) was used to join Al/Mg/Al tri-layered clad sheets, aiming at exploring weldability and identifying failure mode in relation to the welding energy. It was observed that the application of a low welding energy of 100 J was able to achieve the optimal welding condition during USW at a very short welding time of 0.1 s for the tri-layered clad sheets. The optimal lap shear failure load obtained was equivalent to that of the as-received Al/Mg/Al tri-layered clad sheets. With increasing welding energy, the lap shear failure load initially increased and then decreased after reaching a maximum value. At a welding energy of 25 J, failure occurred in the mode of interfacial failure along the center Al/Al weld interface due to insufficient bonding. At a welding energy of 50 J, 75 J and 100 J, failure was also characterized by the interfacial failure mode, but it occurred along the Al/Mg clad interface rather than the center Al/Al weld interface, suggesting stronger bonding of the Al/Al weld interface than that of the Al/Mg clad interface. The overall weld strength of the Al/Mg/Al tri-layered clad sheets was thus governed by the Al/Mg clad interface strength. At a welding energy of 125 J and 150 J, thinning of weld nugget and extensive deformation at the edge of welding tip caused failure at the edge of nugget region, leading to a lower lap shear failure load.

1. Introduction

Lightweighting has been regarded as a key strategy in the automotive and aerospace industries to improve fuel efficiency and reduce anthropogenic environment-damaging, climate-changing, human death-causing[1] and costly emissions [1–6]. It has been reported that the fuel efficiency of passenger vehicles can be enhanced by 6–8% for each 10% reduction in weight [7]. Magnesium (Mg) alloy, as the lightest structural metallic material with a density of ~30% less than aluminum and one fourth of steel, has been increasingly used in the transportation industry to reduce the weight of motor vehicles [1,2,8–12]. However, the concerns about poor corrosion resistance and low room-temperature formability of Mg alloys limit a widespread structural application in transportation industry [13–23]. Recently, roll cladding has been identified as a promising technique to improve the corrosion resistance and formability of Mg alloys [24–31]. In particular, Al-clad Mg alloy sheet can combine the corrosion resistance and formability of an Al alloy with the high strength-to-weight ratio of Mg substrate. Several studies have shown the successful cladding of Al on Mg alloy sheet using hot and cold rolling, which resulted in good surface corrosion resistance and improved formability [24,25,32].

The structural application of these Al-clad Mg alloy sheets inevitably involves welding and joining during manufacturing [33–37]. Due to the challenges of fusion welding in joining Mg alloys, solid-state welding techniques such as friction stir welding (FSW), linear friction welding (LFW), friction stir spot welding (FSSW), and ultrasonic spot welding (USW) are gaining momentum due to their potential of obtaining superior joint properties compared with the fusion welding techniques [33,34,37–46]. USW, involving an ultrasonic high-frequency shear vibration to generate localized heat to soften the material at the weld interface, is an emerging and promising technique in especially joining lightweight magnesium and aluminum alloy sheets compared with the conventional

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[1] According to Science News entitled "Air pollution kills 7 million people a year" on March 25, 2014 at http://news.sciencemag.org/signal-noise/2014/03/air-pollution-kills-7-million-people-year: "Air pollution is not just harming Earth; it's hurting us, too. Startling new numbers released by the World Health Organization today reveal that one in eight deaths are a result of exposure to air pollution. The data reveal a strong link between the tiny particles that we breathe into our lungs and the illnesses they can lead to, including stroke, heart attack, lung cancer, and chronic obstructive pulmonary disease."

http://dx.doi.org/10.1016/j.matdes.2014.05.035
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Table 1
Chemical composition of base materials used in the Al/Mg/Al tri-layered clad sheets in the present study.

Base material	Ce	Mn	Fe	Si	Cu	Mg	Al
Magnesium alloy	0.75	1.73	<0.05	<0.05	<0.05	Bal.	0.2
1060 Aluminum	–	<0.01	0.21	0.09	<0.01	<0.01	Bal.

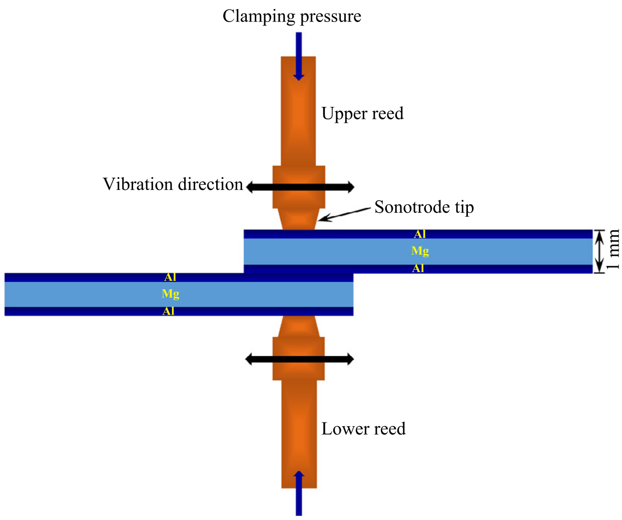

Fig. 1. Schematic diagram of USW of Al/Mg/Al clad sheet using a dual-reed ultrasonic welding system.

resistance spot welding and FSSW due to its low energy consumption and higher efficiency [47–54].

While several studies on the process optimization and mechanical characterization of rolled Al-clad Mg alloy sheets have been reported [24,25,32], to the authors' knowledge, no report on the USW of such clad sheets has been seen in the literature so far. During USW, intense sliding motion along the weld interface by the vibration of welding tips generates heat due to friction and plastic deformation, resulting in adhesion and forming micro-welds which increase in density and spread over the affected area. It is well understood to have a sufficient friction to achieve good bonding at the interface. However, this friction force at the weld interface may generate shear stresses at the pre-existing Al/Mg clad interface and may decrease its strength. It is unknown if it is feasible to join the Al-clad Mg alloy sheets using USW, and whether the frictional heat at the weld interface would cause inter-diffusion at the Al/Mg clad interface and subsequently generate brittle intermetallics such as $Al_{12}Mg_{17}$ and Al_3Mg_2. Also, it is unclear how the generated frictional heat and subsequent softening will affect the sonotrode tip penetration in the clad layer. A deeper penetration may re-expose Mg alloy substrate and therefore increase corrosion susceptibility. Furthermore, it is unclear how failure would occur during the lap shear tensile tests in relation to the welding energy. The purpose of this study was, therefore, to identify the optimum USW parameters and failure mode, so as to achieve the optimal joint strength without damaging protective clad surface layer.

2. Materials and experimental procedure

The materials used in the present study were 0.99 mm thick Al 1060/Mg alloy/Al 1060 tri-layer clad sheets fabricated by a

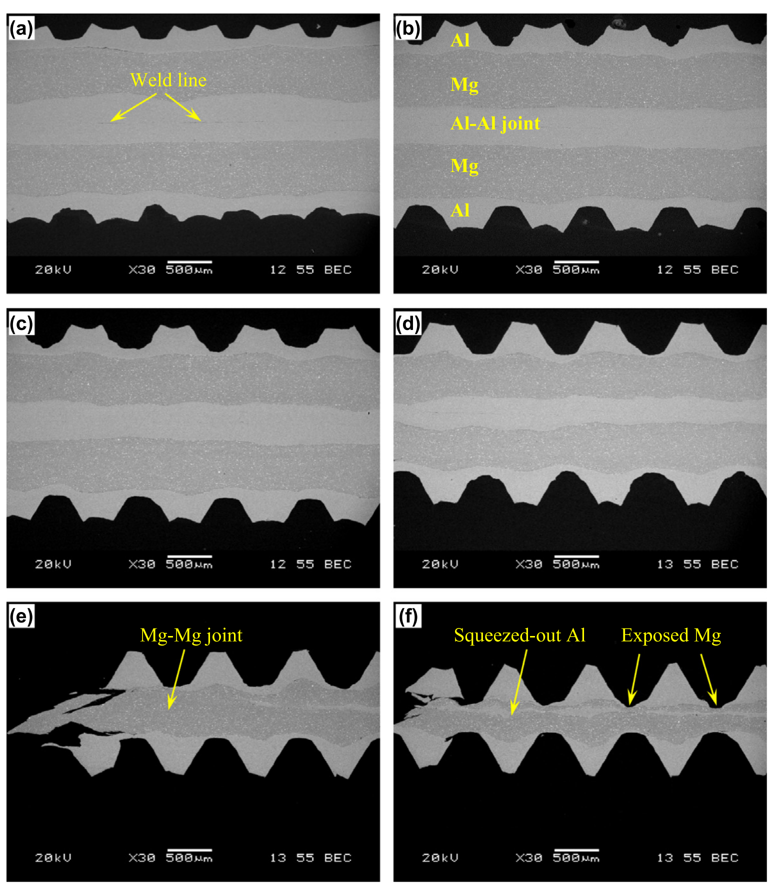

Fig. 2. Typical cross section SEM images of USWed Al/Mg/Al clad sheets at a welding energy of (a) 25 J, (b) 50 J, (c) 75 J, (d) 100 J, (e) 125 J, and (f) 150 J.