Scripta Materialia 126 (2017) 58–62

Contents lists available at ScienceDirect

Scripta Materialia

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

Regular Article

Ultrasonic spot welding of magnesium alloy to titanium alloy

Daxin Ren [a,b], Kunmin Zhao [a,c,*], Min Pan [a], Ying Chang [a], Song Gang [b], Dewang Zhao [d]

[a] School of Automotive Engineering, Dalian University of Technology, Dalian 116024, China
[b] Key Laboratory of Liaoning Advanced Welding and Joining Technology, Dalian University of Technology, Dalian 116024, China
[c] Institute of Industrial and Equipment Technology, Hefei University of Technology, Hefei 230601, China
[d] Department of Engineering Mechanics, Dalian University of Technology, Dalian 116024, China

ARTICLE INFO

Article history:
Received 6 June 2016
Received in revised form 30 July 2016
Accepted 1 August 2016
Available online xxxx

Keywords:
Magnesium alloy
Titanium alloy
Ultrasonic welding

ABSTRACT

This research explores the joining between dissimilar alloys (magnesium alloy and titanium alloy) by ultrasonic spot welding. The tensile shear test shows that the joint strength increases with energy input. The fracture initiates inside magnesium alloy, indicating a high joining strength at the weld interface. Banded grain-refinement is found at the interface on the magnesium alloy side, neither transition layer nor inter-metallic compound layer is identified though. The interfacial temperature exceeds the temperature range for liquefying magnesium alloy. The precipitated aluminum from the liquid-phase magnesium alloy plays a bridging role in ultrasonic welding of magnesium alloy to titanium alloy.

Light metals and alloys have been increasingly used in automotive and aerospace industries to reduce weight, resulting in a great need to join dissimilar materials. There are some difficulties in joining dissimilar light alloys. One major issue when welding dissimilar Al/Mg or Al/Ti alloys is the formation of Al3Mg2, Al12Mg17, AlTi, AlTi3, Al3Ti and other brittle and hard intermetallic compounds in a large quantity [1,2]. These compounds seriously deteriorate the joints mechanical properties [3,4]. When welding such dissimilar light alloys, solid-phase welding or fusion welding with additional alloying element is adopted to refrain from or reduce the generation of intermetallic compounds [5–7]. Another issue is raised when welding dissimilar Mg/Ti alloys due to the severe differences between the base metals in terms of physical, chemical, and metallurgy properties. In other words, Ti does not react with Mg metallurgically, with the solubility of Ti in Mg being less than 0.1%. Moreover, the melting point of Ti is 1668 °C, whereas the boiling point of Mg is only 1090 °C [8–10].

At present, welding of dissimilar Mg/Ti-based alloys mainly involves cold metal transfer welding–brazing, laser welding, friction-stir welding (FSW), and other joining processes [11–13]. In principle, ultrasonic spot welding (USW), a type of solid-phase welding characterized by a lower energy input and a shorter welding time, bonds two surfaces with a frictional interaction produced under pressure by transferring high-frequency vibration waves onto surfaces [13,14]. Research results on ultrasonic welding of similar alloys Al/Al, Mg/Mg and Ti/Ti and dissimilar alloys Mg/Al and Ti/Al have been published [15–18]. It is shown that USW effectively reduces the generation of intermetallic compounds, resulting in high joint strength [19,20]. Besides, some dissimilar alloys or metals, such as Al/Cu, Al/Steel, Mg/Steel and Cu/Ni, have been ultrasonically spot welded and positive results have been achieved [21–24]. However, the joining between dissimilar Mg/Ti-based alloys, which are non-reactive and mutually insoluble, has been little studied. No literature on USW of Mg and Ti alloys has been found. The aim of this work is to ultrasonically weld Mg and Ti alloys and investigate the strength of the weld and the microstructure at the weld interface.

A1.5 mm thick sheet Mg alloy AZ31B (Mg–3Al–1Zn–0.6Mn) and a 1.5 mm thick sheet Ti alloy Ti6Al4V (Ti–5.9Al–4.2 V) are selected for USW. The specimen is 80 mm long and 25 mm wide with the faying surfaces ground using sandpaper, cleaned with ethanol followed by acetone, and dried before joining. The welding of a 10×10 mm^2 tip area is conducted under a clamping pressure of 0.35 MPa, a frequency of 20 kHz, an amplitude of 30 μm, and welding time ranging from 200 to 800 ms at an interval of 100 ms. A hole with a diameter of 0.5 mm is drilled from the side into the specimen of Ti6Al4V as close to the top surface as possible without penetrating it. A thermocouple of 0.5 mm in diameter was inserted into the hole. The interfacial surfaces of the to-be-welded specimens were rubbed using sandpaper. In this manner, the actual measurement position is 0–0.5 mm underneath the Ti surface.

To evaluate the mechanical strength of the joints and identify the optimum joining conditions, tensile shear tests were conducted at room temperature and a constant crosshead speed of 1 mm/min to measure the lap shear failure load. The microstructures and fracture surfaces of the joints were observed using an optical microscope (OM) and a scanning electron microscope (SEM) equipped with energy dispersive X-ray spectroscopy (EDS) and electron backscattered diffraction (EBSD). The element at the interface is line scanned using an electron probe microanalyzer (EPMA).

* Corresponding author at: 2 Ling Gong Road, Dalian 116024, China.
E-mail address: kmzhao@dlut.edu.cn (K. Zhao).

http://dx.doi.org/10.1016/j.scriptamat.2016.08.003
1359-6462/

Seven levels of welding time were adopted to weld Mg/Ti-based alloys. The measured failure load vs. welding time in tensile shear test are plotted in Fig. 1(a). The failure load curve is generally upward with increasing welding time and begins to stabilize after the time exceeds 600 ms. The mean failure load reaches 3.8 kN when the time is 700 ms. However, when the welding time increases up to 800 ms, any excessive heat-vibration combined effect may lead to apparent collapses and cracks on the magnesium alloy surface. Once cracks are initiated, the failure load of the welded joint decreases remarkably. Therefore, although the maximum failure load may exceed 4 kN when adopting a welding time of 800 ms, a wider scatter of the measured failure load is observed. The failure load of Mg/Mg alloy joint (nugget area of 8×6 mm^2) by ultrasonic welding reportedly reaches 4.2 kN [25]. Preliminary fatigue tests were carried out under force-controlled conditions at a load ratio of 0.2 and a frequency of 20 Hz. The applied maximum load levels P_{max} is 60% of the mean static ultimate load. The tests were terminated when specimens were separated. The results in Fig. 1(b) show that the fatigue life can exceeds 10^4 under the welding time of 600 and 700 ms. The fracture mode is partially interfacial and partially transverse-through-thickness crack growth failure. The fatigue property of Mg/Ti joint is very close to that of Mg/Mg and Mg/steel ultrasonic welded joints [19,23].

The alloys based on Mg and Ti, which are mutually insoluble, exhibit large differences in nature. Moreover, the two alloys are difficult to connect directly according to the phase diagrams [8]. However, USW still can achieve high-strength joining without the addition of alloying materials to Mg/Ti-based alloys, indicating a series of reactions between the two alloys improving the joining. In the following sections, the joining mechanism of the interface will be analyzed in detail.

Fig. 2(a) shows the cross section of the welded joint between dissimilar Mg/Ti-based alloys under a welding time of 700 ms. Although Mg is hard to react with Ti metallurgically, good joining is obtained between magnesium and titanium alloys, without lack-of-fusion or any other defect in the weld. Notably, a banded grain-refining zone is found at the interface in the center as shown in Fig. 2(b). When the ultrasonic welding process is operated at a welding time between 300 and 600 ms, the interfacial microstructure of magnesium alloy is similar to that of the base metal. However, a welding time between 600 and 700 ms triggers change of the magnesium alloy microstructure in the weld center. Fig. 2(c) reveals the 3–4 μm grain size of magnesium alloy at the interface and noticeable refinement in comparison with the average 30 μm grain size of the base metal. Similarly, grain refining occurs under a rapid cooling rate in fusion welding of Mg alloys such as laser welding and electron beam welding [26]. Therefore, it can be preliminarily concluded from the grain refining at the interface that the magnesium alloy is locally melted during USW of Mg/Ti alloys.

During USW and FSW, the interfacial morphology is an important strength-determining factor [27,28]. The strength is improved by the mechanical interlocking generated at the complex weld interface, specifically it increases with interface length and interpenetrating feature thickness [19]. On the other hand, the metallurgical reactions in welding dissimilar metals such as Mg/steel [29], Al/steel [21] and Al/Ti [17] can produce layers of intermetallic compounds at the interface. However, studies on grain refining at the interface of magnesium alloy in ultrasonic welding have been rarely reported [19,25,30]. To identify whether the interface forms a metallurgical reaction layer, the element is line scanned and the results are shown in Fig. 2(d). The alloying elements at the interface between Mg/Ti base metals have undergone substantial changes without any elemental transition layer. The EBSD result in Fig. 2(e) also shows no new reaction layer between the grains of magnesium alloy and titanium alloy. These results indicate that the joining between Mg alloy and Ti alloy occurs on a fine micro scale. Some research on Mg—Ti welding reported that Ti—Al intermetallic compound layer can be observed at the joint interface in FSW, laser welding and arc brazing [11–13], but the reaction layer is not observed in USW probably because its heat input is very low compared to those welding methods mentioned above.

The tensile shear test manifested interfacial fracture of the ultrasonically welded joint of Mg/Ti alloys. The fracture surface is divided into two zones shown in Fig. 3(a) and (d). The top zone, approximately 1/3 of the joint area, is where the fracture initiates from. The remains of magnesium alloy are visible on the fracture surface of the titanium side. The microstructures of areas A1 and B1 (corresponding to Fig. 3(b) and (e), respectively) demonstrate plenty of cleavage planes, similar to the shear fracture of lap-welded joint of magnesium alloy. The results of energy spectrum analysis (see the chemical compositions of T1, T2, M1 and M2 in Table 1) reveal: the fracture surfaces of both sides are mainly composed of Mg and Al; the contents of Mg and Al at the fracture surface are close to those of the AZ31 base alloy; the maximum content of Ti on the Ti6Al4V side is only 0.9%. These facts indicate that the Mg/Ti joint fracture initiates from inside the magnesium alloy, which helps explain why the weld strength of dissimilar Mg/Ti-based alloys is close to that of the homogeneous magnesium alloy.

The fracture surfaces in the extension zone, i.e. the bottom 2/3 of the joint area, are much smoother macroscopically. The microstructure of area A2 (corresponding to Fig. 3(c)) reveals numerous bumps on the surface. The bumps are 25–50 μm in size, close to the grain size of the AZ31 base alloy (see Fig. 2). The energy dispersive spectroscopy (EDS) results show that the bumps (T3, T4) are mainly composed of Mg with 20% Ti on average, and the smooth areas (T5, T6) are composed of over 80% Ti and 5–9% Mg. On the magnesium alloy side of the fracture, Ti element is not found in the smooth areas (M3, M4) or in the dimples (M5, M6). These findings demonstrate that the welded joint of dissimilar Mg/Ti-based alloys still exhibits a high joining strength in the fracture extension area. After the joint completely fractures, a portion of the magnesium alloy grains separate from the matrix and remain on the surface of the titanium alloy.

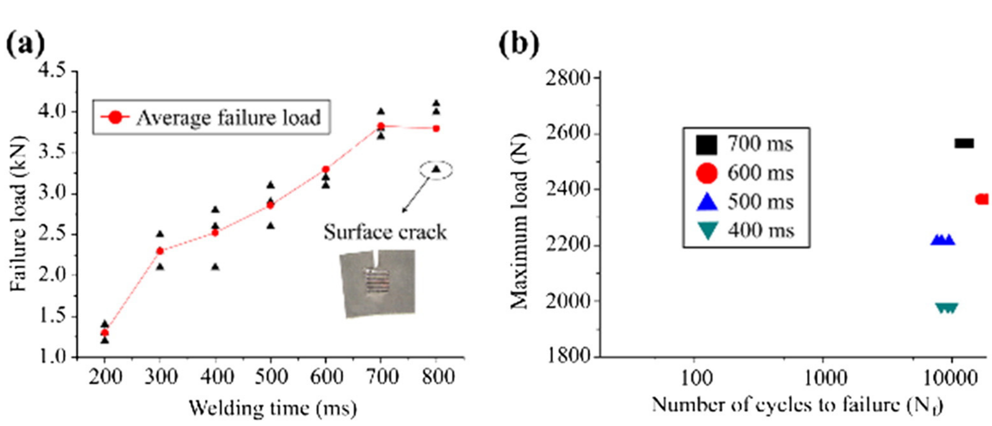

Fig. 1. Strength of the USW Mg/Ti joint: (a) failure load; (b) fatigue life.