Corrosion Science 111 (2016) 793–801

Contents lists available at ScienceDirect

Corrosion Science

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

Marine atmospheric corrosion of Al-Mg joints by friction stir blind riveting

Shengxi Li [a], Haris Khan [b], Lloyd H. Hihara [a,*], Jingjing Li [b,*]

[a] Department of Mechanical Engineering, University of Hawaii at Manoa, Honolulu, HI 96822, USA
[b] Department of Industrial and Manufacturing Engineering, Penn State University, State College, PA, 16801, USA

ARTICLE INFO

Article history:
Received 2 March 2016
Received in revised form 27 April 2016
Accepted 4 May 2016
Available online 16 June 2016

Keywords:
A. Aluminum
A. Magnesium
B. IR spectroscopy
B. XRD
C. Alkaline corrosion
C. Crevice corrosion

ABSTRACT

This paper investigated the atmospheric corrosion behavior of Al-Mg friction stir blind riveting joints exposed at a severe marine test environment. Besides the severe corrosion that occurred on Mg alloy AZ31B-H23, Al alloy 5754-O also corroded in the coupled region because of the alkaline condition generated by the cathodic reaction inside of the crevice. The highly alkaline environment, however, passivated Mg deep inside the crevice. The corrosion products on Mg were identified as magnesium carbonates and that on Al was mainly gibbsite, which was an unusual corrosion product of Al exposed to atmospheric conditions.

1. Introduction

The joining of dissimilar light metals is of increasing demand in the automotive industry for weight reduction and tailored properties. However, the joining of dissimilar metals was limited by traditional fusion welding method which cannot be applied in welding of different metals having vast difference in melting temperatures and may generate brittle intermetallics [1,2]. Friction stir blind riveting (FSBR) is a new mechanical dissimilar material joining method developed by General Motors in 2011 [3], where work materials are softened by the friction stir process to facilitate rivet penetration. FSBR has been successfully applied to the joining of various similar and dissimilar materials, such as Al–Al [4–8], Mg-Al [5], Steel-Mg [9,10], Al-CFRP (carbon fiber reinforced plastics) [11], and CFRP–CFRP [12]. These emerging research activities have suggested that FSBR is suitable for joining various metallic and non-metallic materials that result in joints having superior mechanical properties.

In addition to FSBR, other mechanical riveting methods, such as self-piercing riveting [13], friction self-piercing riveting [14,15], and friction stir riveting [16,17], have also been investigated for joining dissimilar materials. Most of the research, however, focused on process optimization and mechanical behavior of the joints. Very limited research has been reported on the corrosion behavior of these mechanical joints, which is a potential application issue for dissimilar-material joints because of the possibility of galvanic corrosion and crevice corrosion at the joint interface. The galvanic corrosion between the dissimilar material couples have been widely studied in saline environments [18–24]. In these couples, the less noble material usually experiences severe corrosion and the more noble material is protected. However, it was found in the present work that the galvanic couple between Al and Mg behaves differently from conventional understandings when a crevice forms between the two materials.

The Al-Mg dissimilar joints were selected in the present work because of great interests in the automobile industry. While Al alloys have found a wide range of applications as lightweight and high-strength structural materials, Mg alloys are also gaining interests as they are considered as the lightest structural metallic materials (approximately 34% lighter than Al) and provide an attractive high strength to weight ratio for automotive applications. However, Mg alloys can be used only in a few automotive parts [25] because of the limitations due to their mechanical properties, which therefore, requires the joining of Mg with other structural materials, such as Al. Besides the specific choice of the materials, the selection of a severe marine environment for exposure tests was due to the large presence of airborne salt particles in such environ-

* Corresponding authors.
E-mail addresses: hihara@hawaii.edu (L.H. Hihara), lj8@hawaii.edu (J. Li).

http://dx.doi.org/10.1016/j.corsci.2016.05.009

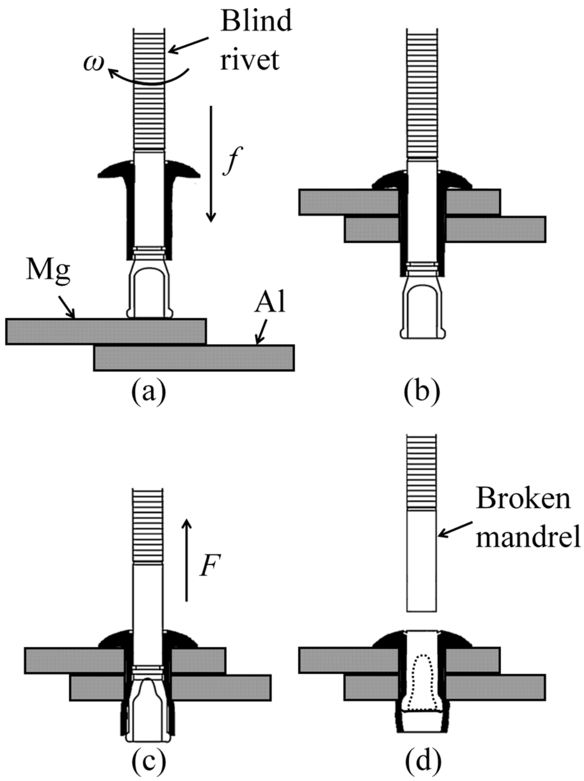

Fig 1. Illustration of the FSBR process [7]: (a) rotating blind rivet approaching the workpieces; (b) frictional penetration of the rivet; (c) pulling out the mandrel; and (d) completion.

ment [26,27] and their great influence on the corrosion behavior of metallic materials [28–32].

The present study aims to 1) identify the various types of corrosion products that formed in the Al-Mg FSBR joint exposed in a marine environment, and 2) elucidate the corrosion mechanism through the characterization of corrosion products. The results will enhance the understanding of corrosion behavior not only in FSBR joints but also in other mechanical joints constituted with dissimilar metals.

2. Experimental

2.1. Materials and FSBR joining

The raw materials used were Mg AZ31B-H23 and Al 5754-O with chemical compositions shown in Table 1. Fig. 1 illustrates the FSBR process for joining the Mg and Al sheets. The Al-Mg FSBR joints were formed on a computer numerical control (CNC) machining center (model: Bridgeport Discovery 308) using 1 mm thick Mg sheets and 3 mm Al sheets. Each work piece was 38 mm wide and 127 mm long. The overlap region had a size of 38 mm × 38 mm. The blind rivet with a diameter of 6.4 mm was made of mild steel with zinc coating. The spindle speed was 5000 rpm and the feed rate was 120 mm/min.

2.2. Outdoor exposure

The Al-Mg FSBR joints (in triplicate) including the rivets were exposed to a severe marine test site located in the Marine Corps Base Hawaii (MCBH) in Kaneohe, Hawaii. This test site is maintained by the Hawaii Corrosion Laboratory and is considered as a severe marine site with regards to corrosion rates. The test site is located within 40 m of a shoreline with waves breaking consistently throughout the year. The average temperature and relative humidity are 23.6 °C and 77%, respectively. The average chloride (Cl^-) deposition rate was 2900 mg/m^2/day and the sulfate (SO_4^{2-}) deposition rate was 390 mg/m^2/day, which were determined using the conventional dry chloride candle method. The corroded joints were retrieved to the laboratory after 6-month exposure for characterization. All three joints showed similar corrosion characteristics, however, only one was characterized.

2.3. Corroded sample characterization

The corrosion products inside the crevice were revealed by pulling the joint to fracture using a tensile machine. The surfaces of the corroded Mg and Al sheets were first characterized using a JEOL JXA–8500F field emission scanning electron microscope (FE-SEM) with energy dispersive spectroscopy (EDS) capability. Then, corrosion products were scraped from the Al and Mg sheets and ground into fine powders using an agate pestle and mortar. The powder samples were characterized with Fourier transform infrared spectroscopy (FTIR, Jasco FT/IR 4100) and powder X-ray diffraction (XRD, Rigaku MiniFlex™ II) to identify the compositions of the corrosion products.

The corroded Al sheet was also chemically cleaned using the procedures and solutions described in ISO 8407: 2009 [33]. Three pristine Al sheets were also cleaned together with the corroded sample. Multiple cleaning cycles were employed until the mass loss of the corroded sample between cleaning cycles was equal to, or less than, the average mass loss of the pristine samples. The cleaned sample was then characterized using the same FE-SEM.

2.4. Microstructural characterization

The Mg and Al sheets that were in contact with the rivet were sectioned from the Al-Mg FSBR joint using a low-speed diamond saw for microstructural characterization. The sectioned samples were mounted in epoxy resin (BUEHLER Epoxicure); ground with 600 and 1200 grit SiC grinding paper; and polished with 9.0, 3.0, and 1.0 μm polycrystalline diamond suspensions (METADI SUPREME, BUEHLER). The Mg sample was polished with isopropanol as a lubricant. After polishing, the samples were ultrasonically cleaned in isopropanol for 5 min and dried under cold air.

The polished samples, especially the regions that were in close contact with the rivet, were first characterized using FE-SEM. Then, the Mg sample was etched using an Acetic Picral reagent [34,35] to reveal grain boundaries. The grain boundaries of the Al sample were revealed using the Baker's etching method [36,37]. The Al sample was oxidized in a solution consisting of 5 ml HBF_4 (48%, Sigma-Aldrich) in 200 ml water at a current of 0.2 A/cm^2 for 40–80 s. Then, the grain structure of the etched/oxidized samples were observed under an optical microscope (AxioPlan, Zeiss). Notice that the grain

Table 1
Chemical compositions (wt.%) of the raw materials.

Material	Si	Fe	Mn	Zn	Cu	Ti	Cr	Ni	Al	Mg
AA5754-O	0.4	0.4	0.5	0.2	0.1	0.15	0.03	–	balance	2.6
AZ31B-H23	0.009	0.004	0.28	0.9	–	–	–	0.0008	2.95	balance