Journal of Materials Processing Tech. 258 (2018) 239–250

Contents lists available at ScienceDirect

Journal of Materials Processing Tech.

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

Effect of heat treatment on bonding strength of aluminum/steel bimetal produced by a compound casting

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ARTICLE INFO

Keywords:
Compound casting
Heat treatment
Aluminum alloy
Steel
Bimetal
Bonding strength

ABSTRACT

A compound casting process combined with hot-dip galvanizing was used to produce an aluminum/steel bimetal, obtaining a superior metallurgical interface that mainly consisted of τ_6-$Al_{4.5}FeSi$, Al-Zn eutectic and Si phases. Under as-cast condition, the aluminum/steel bimetal had a relatively low bonding strength, resulting from the poor morphology and size of the τ_6-$Al_{4.5}FeSi$ phase and the Si particles. An appropriate heat treatment procedure greatly improved the interfacial microstructure and bonding strength of the aluminum/steel bimetal, and the phase compositions in the interface were nearly similar to that of the as-cast condition. The excessive heat treatment promoted the excessive growth and cracks of the interface layer, sharply weakening the bonding strength of the aluminum/steel bimetal. With a solution temperature of 500 °C for 2 h, the shear strength of the aluminum/steel bimetal significantly increased by 39% in comparison with that of the as-cast sample, which was mainly attributed to the improvements of the morphology and size of the τ_6-$Al_{4.5}FeSi$ phase and the Si particles. No excessive growth of the interface layer and the absent of the crack defect were also responsible for the improvement of the shear strength of the aluminum/steel bimetal.

1. Introduction

Currently, a larger number of bimetals that are constituted by different alloys are in increasing demand in various industrial applications, such as Al/Steel, Al/Fe, Al/Al, Al/Mg, and Al/Cu, as they can provide different expected properties from the different alloys. Many researchers have carried out the investigations on different bimetallic materials. Jiang et al. (2015) fabricated the steel/aluminum bimetallic castings by a compound casting process. Liu et al. (2015) achieved the dissimilar material joining of 5052 aluminum alloy and ST07Z galvanized steel using a Nd:YAG laser. Liu et al. (2013) prepared the Al-7Si/gray iron bimetal by using a compound casting. Viala et al. (2002) investigated the interface of aluminium/iron bimetallic castings. Wang et al. (2014) obtained the 8090/3003 bimetal slab of aluminum alloys with a modified direct-chill casting. Xu et al. (2017) studied the effect of heat treatment and initial thickness ratio on spin bonding of 3A21/5A03 composite tube. Yang et al. (2017) reported the AZ31 magnesium/3003 aluminum alloy joints with a contact-reaction brazing. Fu et al. (2015) produced dissimilar metals of 6061-T6 aluminum alloy and AZ31B magnesium alloy with a friction stir welding. Sahu et al. (2016) evaluated the influence of plate position, tool offset and tool rotational speed on mechanical properties and microstructures of dissimilar Al/Cu friction stir welding joints. Lee et al. (2013) fabricated the Al/Cu composite with a hydrostatic extrusion. Amidst, the aluminum/steel bimetal may be a promising solution for the automotive and aircraft components, cryogenic and chemical tanks, etc, as indicated by Jin and Hong (2014) and Kang et al. (2007). On the one hand, Jiang et al. (2014) has indicated that aluminum alloys contribute to weight reduction as well as high thermal and electrical conductivity, and Lu and Zhang (2017) also pointed out these advantages of the aluminum alloys. On the other hand, Silverstein and Eliezer (2015) and Fayomi et al. (2015) have proposed that steel can provide high strength, good creep resistance, excellent corrosion and abrasion resistance. However, there is always a challenge for the fabrication of the aluminum/steel bimetal that possesses an excellent metallurgical interface. That can be explained by the fact that the aluminum and the steel are incompatible, because their thermal-physical properties have great differences; meanwhile, they are easy to oxidize (Springer et al., 2011), and Zheng et al. (2016) also presented this problem. Peng et al. (2017a,b) reported that hot-dip galvanizing is a very effective method to protect the steel from corrosion and oxidation. It is noted that the aluminum/steel bimetal with an excellent metallurgical interface is of great importance to obtain a superior bonding strength (Bouayad et al., 2003; Jiang et al., 2015), and the bonding strength of the aluminum/steel bimetal is a key consideration during the practical application process of the aluminum/steel bimetal. In general, the aluminum/steel bimetal under as-cast

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https://doi.org/10.1016/j.jmatprotec.2018.04.006
Received 8 February 2018; Received in revised form 2 April 2018; Accepted 4 April 2018
Available online 05 April 2018
0924-0136/

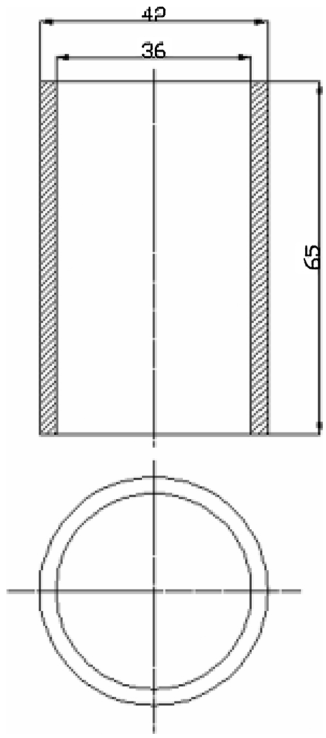

Fig. 1. Shape and sizes of the steel inserts (unit: mm).

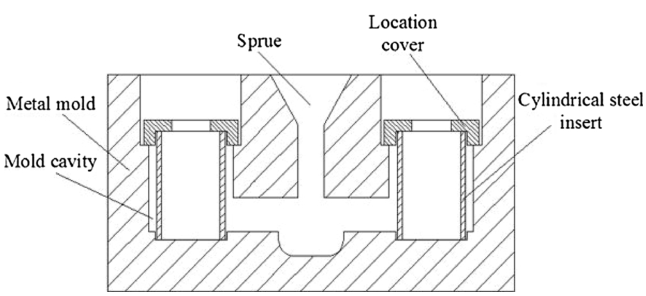

Fig. 2. Schematic illustration of the experimental setup.

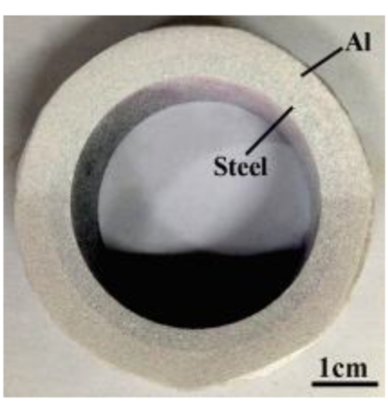

Fig. 3. Marco-characterization of the aluminum/steel bimetal under as-cast condition.

condition has a relatively low bonding strength, which limits the application of the aluminum/steel bimetal. Although the bonding strength of the bimetal may be optimized via the regulation of the process parameters adjusting the layer thicknesses of the interface and intermetallic compounds (Nambu et al., 2009), they can also be further improved by an appropriate heat treatment procedure, as reviewed by Barabash et al. (2014) and Cao et al. (2016). Consequently, the heat treatment process plays an important role in the preparation of the aluminum/steel bimetal. However, there is basically an unexplored field in the investigation of the effect of the heat treatment on the bonding strength of the aluminum/steel bimetal.

In the present work, a compound casting process combined with the hot-dip galvanizing was used to produce the aluminum/steel bimetal, and a heat treatment process was then applied in the aluminum/steel bimetal in order to further improve the bonding strength of the aluminum/steel bimetal. The effects of the heat treatment on microstructures, mechanical properties, and fracture behaviour of the aluminum/steel bimetal were systematically investigated, obtaining an appropriate heat treatment procedure for the fabrication of the aluminum/steel bimetal with the superior bonding strength.

2. Experimental procedure

2.1. Materials

The ZL114A aluminum alloy (Al-6.75Si-0.63 Mg-0.14Ti-0.084Fe in mass%) and the structural carbon steel (Fe-0.24 C-0.65 Mn-0.37Si-0.03 P-0.02 S-0.25Ni-0.25Cr in mass%) were respectively chosen as a molten bath and a solid insert to fabricate the aluminum/steel bimetal. A zinc alloy (Zn-0.1Ni in mass%) was used to obtain a coating on the surface of the carbon steel inserts for the hot-dip galvanizing process.

Fig. 1 shows the shape and sizes of the steel inserts. Prior to the hot-dip galvanizing process, the external surfaces of the carbon steel solid inserts were first treated by using silicon carbide papers, followed by rinsing with the hydrochloric acid and ethanol solutions.

2.2. Preparation of aluminum/steel bimetal

The ZL114A aluminum alloy ingots were melted with an electrical resistance furnace, and they were refined by using an argon gas when the temperature of the aluminum melt was up to 740 °C. The steel inserts were first preheated at 300 °C, and they were then hot-dipped into a zinc bath at 450 °C holding for 5 min. Subsequently, the steel inserts with the zinc coating were quickly placed inside a metal mold with a preheat temperature of 300 °C. The aluminum molten metal was then poured into the metal mold at 740 °C, thereby obtaining the aluminum/steel bimetal after solidification. Fig. 2 presents a schematic illustration of the experimental setup.

2.3. Heat treatment process

The prepared aluminum/steel bimetals were subjected to a heat treatment process including a solution treatment and a subsequent aging treatment, mainly based on the heat treatment process of the cast Al-Si alloy (Jiang et al., 2012). Different solution temperatures and solution times were investigated in this work. The solution temperatures were respectively 460, 500 and 540 °C holding for 6 h. The solution times chose 2, 6 and 10 h at 500 °C. Next, the aluminum/steel bimetals were quenched into the 80 °C hot water, followed by suffering from the aging treatment at 165 °C for 6 h, and they were finally cooled in air.

2.4. Microstructural characterizations and mechanical properties

The metallographic samples were first ground and polished, and they were then etched using a 0.5% hydrofluoric acid solution. A Quanta 400 scanning electron microscope (SEM) was used to observe the microstructure of the aluminum/steel bimetal. The chemical compositions at the interface of the aluminum/steel bimetal were detected by the energy dispersive spectroscopy (EDS) analysis attached to the SEM. The analyses of intermetallic phases in the reaction layer were also performed with a X-ray diffraction (XRD) analysis.