Materials and Design 64 (2014) 287–293

Contents lists available at ScienceDirect

Materials and Design

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

Interfacial microstructures and properties of aluminum alloys/galvanized low-carbon steel under high-pressure torsion

Yang Liu [a], Xiufang Bian [a,*], Kai Zhang [a], Chuncheng Yang [a], Le Feng [a], Hyoung Seop Kim [b], Jing Guo [b,c]

[a] Key Laboratory for Liquid-solid Structural Evolution and Processing of Materials, Ministry of Education, Shandong University, Jinan 250061, PR China
[b] Department of Materials Science and Engineering, Pohang University of Science and Technology, Pohang 790-784, South Korea
[c] College of Mechanical and Electronic Engineering, Shandong Agricultural University, Taian 271018, PR China

ARTICLE INFO

Article history:
Received 5 May 2014
Accepted 24 July 2014
Available online 8 August 2014

Keywords:
Aluminum alloys
Low-carbon steel
Hot-dipping
Interface
High pressure torsion

ABSTRACT

A new composite processing technology characterized by hot-dip Zn–Al alloy process was developed to achieve a sound metallurgical bonding between Al–7 wt% Si alloy (or pure Al) castings and low-carbon steel inserts, and the variations of microstructure and property of the bonding zone were investigated under high-pressure torsion (HPT). During hot-dipping in a Zn–2.2 wt% Al alloy bath, a thick $Al_5Fe_2Zn_x$ phase layer was formed on the steel surface and retarded the formation of Fe–Zn compound layers, resulting in the formation of a dispersed Al_3FeZn_x phase in zinc coating. During the composite casting process, complex interface reactions were observed for the Al–Fe–Si–Zn (or Al–Fe–Zn) phases formation in the interfacial bonding zone of Al–Si alloy (or Al)/galvanized steel reaction couple. In addition, the results show that the HPT process generates a number of cracks in the Al–Fe phase layers (consisting of Al_5Fe_2 and Al_3Fe phases) of the Al/aluminized steel interface. Unexpectedly, the Al/galvanized steel interface zone shows a good plastic property. Beside the Al/galvanized steel interface zone, the microhardnesses of both the interface zone and substrates increased after the HPT process.

1. Introduction

Aluminum alloys and steels are indispensable engineering materials because they have good mechanical properties and relatively low material costs in many applications [1]. As a result of more stringent requirements for improved fuel economy and emissions, there is a growing trend to substitute light alloy for conventional steel or cast iron in the automotive industry [2]. Bimetallic composites consisting of light alloys and steels/cast iron can meet the need for high strength and reduce weight to improve fuel economy and emissions, so they possess a great potential for future developments in automotive technology [3–5].

In order to produce a bimetallic composite with good mechanical properties, several composite casting techniques have been applied. The chemical reaction is difficultly triggered between Al and iron when pure Al melt is directly poured to surround the iron insert without pretreatment [6]. Viala et al. [7,8] manufactured bimetallic automotive components consisting of light alloys and cast iron by using the combination of Al-Fin process and gravity casting. Bouayad et al. [9] produced such bimetallic composites using high pressure die casting. The crucial point in the composite casting techniques is the liquid/solid interface between light alloys and ferrous metals substrate. A good wettability of solid substrates is essential in achieving good metallurgical bonding at the interface. In order to improve the wettability of solid substrates, an interlayer coated on the substrate surface has been a common approach.

The Al-Fin process is a method of coating Al alloys on the surface of ferrous metals by hot-dipping [7]. The Al-Fin bond is a bond between an Al alloy and a ferrous metal. The effect of hot-dipping bath composition on the morphology of the interfacial bonding zone is important. The addition of Silicon into the Al alloy bath has a significant influence on the continuous intermediate layer, which not only produces flat morphology from the classical tongue-shaped one in the interface between the intermediate layer and the steel substrate, but also affects the growth of the intermediate layer [10–12]. In the liquid/solid diffusion couple, Si decelerates the growth of η phase in the intermediate layer. In contrast, Springer et al. [13] presented that Si can accelerate the growth of η phase in the intermediate layer for the solid/semisolid diffusion couples. The effect of Mn on the interface has also been studied. Choi et al. [14] found that additional content Mn can make the thickness of the intermetallic layer increase comparing to the Al alloy without Mn at the interface between a low Si Al alloy and STD61 steel. Our previous work [15] has also demonstrated that

* Corresponding author. Tel.: +86 531 88392748; fax: +86 531 88395011.
E-mail address: xfbian@sdu.edu.cn (X. Bian).

http://dx.doi.org/10.1016/j.matdes.2014.07.053
0261-3069/

the addition of Mn facilitated the formation and growth of the α-$Al_{15}(Fe_xMn_{1-x})_3Si_2$ phases and the growth of the continuous metallurgical bonding layer at the Al–7 wt% Si/gray iron interface, which can improve the properties of the Al/Fe interface.

On the other hand, there are many reports that zinc or zinc alloys can also serve as a good interlayer former to achieve a sound joint of dissimilar metals [16–19]. Various methods have been investigated for coating the zinc or zinc alloy interlayers on the surface of the base metal, such as electroplating [16], electroless plating [17], and hot-dipping [18,19]. The zinc or zinc alloy interlayer can not only protect the base metal from oxide in air, but also improve the wettability of the base metal. This creates a salutary environment and conditions for interface reactions between dissimilar metals. Zinc coating on steel is also used in numerous applications especially in the automotive industry to improve the corrosion resistance of steel used for car bodies [20]. Meanwhile, many studies have been reported to join Al alloy to zinc-based coated steel by laser welding-brazing (LWB), friction stir welding (FSW), cold metal transfer (CMT), laser-tungsten inert gas (TIG) hybrid welding, etc. [21–25], but very little work has been done on the composite casting. How to achieve an excellent metallurgical bonding between Al alloys and low-carbon steel still is quite a challenging subject.

In this study a new composite processing technology characterized by an auxiliary hot-dip Zn–Al alloy process was developed in order to achieve a sound metallurgical bonding between Al alloy or pure Al and low-carbon steel. In order to extent the application sphere of the Al/steel bimetal composite under high pressure environment, the variations of microstructure and properties were investigated for the Al/aluminized steel and the Al/galvanized steel samples after high-pressure torsion (HPT) process.

2. Experimental procedure

Steel samples (diameter 3 mm × length 100 mm) were cut out from a low-carbon steel bar (containing 0.06–0.12 wt% C) coated a pure zinc coating by electroplating. Prior to immersing the samples in liquid Zn–2.2 wt% Al bath at 723 ± 10 K for various time, all the surface of the steel samples were polished in order to remove surface ZnO layers and cleaned in ethanol. The thickness of the electroplated zinc coating was approximately 5 μm after polishing. Then, the hot-dip galvanized steel samples were moved away from the liquid Zn–Al bath and fastened rapidly on a permanent mould preheated at 473 K, respectively. Si, 0.3–0.45 wt.% Mg, 0.2 wt.% Ti, and Al) was poured into the mould at 993 ± 10 K. These liquid Zn–Al alloy, Al and Al–Si alloy were melted in an intermediate frequency furnace and held at a setting temperature in a resistance furnace.

The Al/steel samples were cut into small disks (diameter 10 × length 1.5 mm) for the HPT process. These small disks were placed in a circular shallow hole of the lower HPT anvil, as shown in Fig. 1 [26]. Then, the lower anvil with the disk sample was raised to contact the upper anvil having the same shallow hole at the center. While applying a pressure of 5 GPa at room temperature, the lower anvil was rotated at a rotation speed of 1 rpm and the rotation was terminated after 1 turn. In order to evaluate the effect of the HPT process on the strength of the bonding interface, the Vickers micro-hardness test (model DHV-1000) was performed along the thickness direction of the original and treated samples with a low indentation load of 10 g.

For the composition and microstructure analyses, vertical or horizontal cross sections were prepared by successive grinding and polishing. The vertical and horizontal cross section samples were cut from the Al–Si alloy or Al/galvanized steel composite and mounted using epoxy by a mounting press. In order to further

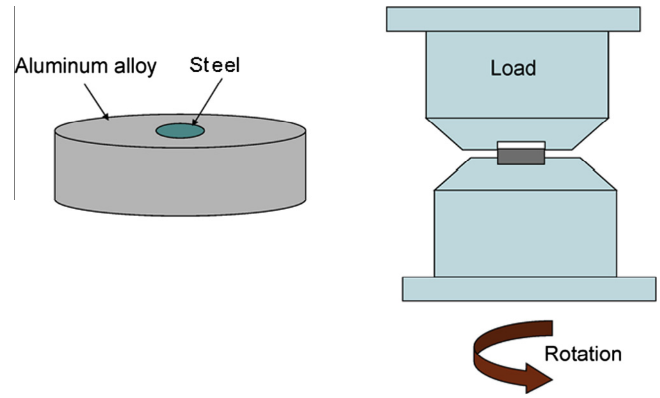

Fig. 1. Schematic of the HPT process.

analyze the interfacial bonding zone, the interfacial microstructure of each sample was examined using an optical microscope (OM) and scanning electron microscopy (SEM). The phases were chemically characterized to evaluate the nature of the intermetallics using energy dispersive spectroscopy (EDS).

3. Results

3.1. Growth and microstructure of the hot-dip galvanized coating

The hot-dip Zn–Al alloy process is a vital step for achieving a sound metallurgical bonding between Al alloy castings and steel inserts, so it is essential to study the growth and microstructure of the hot-dip galvanized coating.

Fig. 2 exhibits SEM images of the vertical section of the steel sample after hot-dipping in Zn–2.2 wt% Al melt at 723 K for 300 s and the thicknesses of the hot-dip galvanized coating and the diffusion layer as a function of hot-dip time. The average thickness of the light gray Zn–Al coating on the surface of the steel substrate is approximately 292 μm. The diffusion layer consisting of some dark gray phases was formed in the interface between the Zn–Al coating and steel substrate after hot-dipping. The dark gray phase exhibits continuously graded morphology and is strongly attached to the steel substrate. However, some pores exist in the region adjacent to the steel substrate. They are attributable to the steel particles dissolved from the steel substrate during hot-dipping and departed during grinding and polishing. The other parts of the dark gray phases exhibit dispersive distribution in the Zn–Al coating. The microstructure of the interface between the Zn–Al coating and steel substrate can be observed clearly in Fig. 2(b). The chemical compositions of these interfacial phases were identified using spot scanning of SEM-EDS, as shown in Table 1. According to the characterization of the ternary solid phase in Al–Fe–Zn system [27,28], the continuous layered phases were identified as $Al_5Fe_2Zn_x$, and the dispersive phases were identified as Al_3FeZn_x. It can be seen that the average thickness of the hot-dip galvanized coating increases with increasing hot-dip time, and the average thickness of the diffusion layer presents the same trend (Fig. 2(c)).

3.2. Observation of the Al/galvanized steel and Al–Si/galvanized steel interfaces after pouring

The objective of this part is to analyse the effect of the different composition of the Al melts on the microstructure forming at the Al alloy casting/galvanized steel insert interface.

Fig. 3 presents the optical micrographs of the Al–Si/galvanized steel and Al/galvanized steel interfaces obtained from the samples poured from Al–Si alloy and pure Al melts, respectively. The