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Effects of hot-dip galvanizing and aluminizing on interfacial microstructures and mechanical properties of aluminum/iron bimetallic composites

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ABSTRACT

In this paper, the aluminum/iron bimetallic composites were successfully fabricated using ZL114A alloy and gray cast iron by hot-dip galvanizing and aluminizing method, and the effects of the hot-dip galvanizing and aluminizing on interfacial microstructures and mechanical properties of the aluminum/iron bimetallic composites were investigated. Without the application of the hot-dip galvanizing and aluminizing, the gaps and oxide films were formed at the interface between the aluminum and the iron, resulting in a poor mechanical bonding without a reaction layer between the aluminum and the iron. In the case of the hot-dip galvanizing and aluminizing, a relatively uniform and compact reaction layer that mainly consisted of Fe_2Al_5, τ_{10}-$Al_9Fe_4Si_3$, $FeAl_3$, τ_5-Al_8Fe_2Si and τ_6-$Al_{4.5}FeSi$ intermetallic compounds was formed between the aluminum and the iron. The curved interface had a thicker reaction layer up to about 53 μm compared to the straight interface with an average thickness of approximately 25 μm. The average nano-hardnesses of the straight and curved interfaces between the aluminum and the iron reached respectively 10.79 and 10.49 GPa, which were obviously higher than those of the iron and aluminum base metals, especially the aluminum base.

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1. Introduction

Currently, aluminum alloys are extensively employed in the automotive industry because of their low density, excellent castability, good corrosion resistance and high strength to weight ratio, etc [1–4]. However, they are difficult to wholly meet some practical requirements in industrial applications, such as pistons and cylinders used in the automotive industry, because they suffer from severe cyclic thermal and mechanical loads that are simultaneously generated by the localised intense fire, explosion pressure as well as the clamping of the components. It is well known that the cast iron can adapt to the above adverse working condition well due to its high wear resistance and strength, excellent vibration damping, low cost, and excellent machinability [5–7]. Therefore, the aluminum/iron bimetallic composites that are constituted by an assembly of different layers consisting aluminum and iron sections as a combined structure may be a promising solution for the industrial applications, particularly in the automotive industry, where each layer can provide different expected properties. However, preparing the aluminum/iron bimetallic composites is always a challenging concept as a result of larger differences in the thermal-physical properties for aluminum and iron [8,9], meanwhile, aluminum and iron are tend to oxidize, which lead to the incompatible and poor bonding between the aluminum and the iron. It has been proposed that an excellent metallurgical interface is of great importance to guarantee the sealing, heat transfer and mechanical properties for the bimetallic composites [10].

There are a number of attempts to prepare the aluminum/steel bimetallic composites [11–14], but few studies about the aluminum/iron bimetallic composites have been reported [15,16]. Although steel and iron all belong to Fe–C alloys, the alloy composites have a significant effect on the formations of intermetallic compounds between the Al and Fe [8]. Furthermore, the knowledge with respect to how to control the oxidization of the cast iron, to improve the incompatible as well as to obtain an excellent metallurgical interface between the aluminum and the iron are also incomplete at present.

In this work, the ZL114A aluminum alloy and gray cast iron were

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used to prepare the aluminum/iron bimetallic composites. The gray cast iron inserts were treated using hot-dip galvanizing and aluminizing method in order to protect the surface of the cast iron from the oxidation and to obtain an excellent metallurgical bonding between the aluminum and the iron. The object of the present work is to provide a new process to prepare the aluminum/iron bimetallic composites and to investigate the effects of the hot-dip galvanizing and aluminizing on the interfacial microstructures and mechanical properties of the aluminum/iron bimetallic composites. Moreover, the formation mechanism of the interface of the aluminum/iron bimetallic composites were also studied.

2. Experimental procedures

2.1. Materials

The gray cast iron and ZL114A aluminum alloy that were respectively used as a solid insert and a molten bath were used to prepare the aluminum/iron bimetallic composites, the chemical compositions of which are presented in Tables 1 and 2, respectively. The zinc alloy containing 0.1 wt% Ni and ZL114A aluminum alloy were respectively used to as the hot-dip galvanizing and aluminizing materials for the iron inserts. Here, the function of the addition of Ni in the zinc alloy was used to better protect the surface of the cast iron from the oxidation.

The cylindrical iron inserts with a 76 mm diameter, a 4 mm wall thickness and a 134 mm height were prepared using a centrifugal casting method, the surfaces of which have many salient points in order to enhance the bonding between the aluminum and the iron. Fig. 1 presents the photo and surface morphology of the cylindrical iron insert used in this study. The surfaces of the cylindrical iron inserts were first cleaned with a shot blasting machine and then rinsed using a 0.5 mol/l hydrochloric acid and an ethanol, respectively.

2.2. Fabrication process of composites

Fig. 2 illustrates a schematic illustration of the experimental setting. A preheated ZL114A aluminum ingot was placed inside a stainless steel crucible with a preheating temperature of 300 °C to melt. The ZL114A aluminum melt was refined using the argon gas as the temperature of the molten metal reached 740 °C. Prior to pouring process, the iron inserts that were preheated at 400 °C were first immersed into the molten metal of the zinc alloy at 500 °C for 5 min and then immersed into the molten metal of the ZL114A aluminum alloy at 760 °C for 10 min. Afterwards, the iron inserts which were treated using the hot-dip galvanizing and aluminizing were rapidly placed inside a sand mold to pouring by the molten ZL114A aluminum metal at 740 °C. The fabrication of the aluminum/iron bimetallic composites was completed after solidification. Meanwhile, a comparative experiment without hot-dip galvanizing and aluminizing was also performed with a same experimental condition.

2.3. Microstructural characterizations

In order to investigate interfacial microstructures that include the curved interface corresponding to the salient point and the straight interface between the salient points in the aluminum/iron bimetallic composites, metallographic samples were first cut from the aluminum/iron bimetallic composites using an electrical discharge machine and then polished. A 0.5% hydrofluoric acid solution was used to etch the metallographic cross-sections of the metallographic samples. An Me F-3 metallographic microscope and a Quanta 400 scanning electron microscope (SEM) equipped with an energy-dispersive X-ray spectroscopy (EDS) were used to observe the interfacial microstructures of the metallographic samples. The chemical compositions of the interfacial microstructures were examined by the EDS analysis.

Table 1
Chemical composition of the gray cast iron (wt.%).

Element	C	Mn	Si	P	S	Cu	Cr	Fe
Content	3.22	0.86	1.92	0.13	0.05	0.41	0.29	Balance

Table 2
Chemical composition of the ZL114A aluminum alloy (wt.%).

Element	Si	Mg	Ti	Fe	Al
Content	6.75	0.63	0.14	0.084	Balance

2.4. Mechanical properties

Nano-indentation tests were performed to examine the nano-hardness distributions at the interface zone including the straight and curved interfaces of the aluminum/iron bimetallic composites using a high-precision nano-hardness scratch tester (TI 750, Hysitron, American) with a test force of 6000 μN for a dwell time of 5s.

3. Results

3.1. Interfacial microstructures without hot-dip galvanizing and aluminizing

To compare the effects of with and without hot-dip galvanizing and aluminizing on the interface of the aluminum/iron bimetallic composites, the aluminum/iron bimetallic composites without hot-dip galvanizing and aluminizing were also prepared. Fig. 3 shows SEM micrograph and EDS analysis of the straight interface of the aluminum/iron bimetallic composites without hot-dip galvanizing and aluminizing. As can be seen from Fig. 3a, a large gap is obviously observed at the straight interface of the aluminum/iron bimetallic composite without the hot-dip galvanizing and aluminizing. Furthermore, the oxide film is also detected on the interface between the aluminum and the iron, as shown in Fig. 3b and c. The EDS line scan that is presented in Fig. 3d shows that the Al, Fe and Si elements do not clearly diffuse at the interface between the aluminum and the iron, but the concentration of the O element is detected at the interface, which suggests that the reaction of the aluminum with iron has not occurred, forming a poor mechanical bonding between the aluminum and the iron.

Fig. 4 shows SEM micrograph and EDS analysis of the curved interface of the aluminum/iron bimetallic composites without hot-dip galvanizing and aluminizing. It is evident that the gaps are also observed at the curved interface between the aluminum and the iron, as shown in Fig. 4a. The EDS analysis also imply that no reaction layer between the aluminum and the iron is generated at the curved interface, and the O element has a concentration at the interface, as shown in Fig. 4b and c. According to the results of Figs. 3 and 4, it means that a poor mechanical bonding without a metallurgical interface between the aluminum and the iron is obtained as the hot-dip galvanizing and aluminizing is absent.

3.2. Interfacial microstructures with hot-dip galvanizing and aluminizing

The SEM micrographs and EDS analysis of the straight interface

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