Microstructure and Mechanical Properties of Al/Steel Bimetal Composite Produced by Compound Casting

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Abstract: In order to obtain Al/steel bimetal composite materials with good metallurgical combination, the process of Al/steel compound casting is proposed. The solid heat-resisting steel plate is dipped into liquid aluminum for 15min and then put it into the casting mould and pour the fresh liquid ZL102 of 760℃ around it. After coasting, the sample is carried out to heat preservation treatment. During hot-dipping in an Al alloy bath, a 32μm thick diffusion was formed between the steel plate and the aluminum coating. During the composite casting process, complex interface reactions were observed for the $Al_{4.5}FeSi$ phases formation in the interfacial bonding zone. Analysis found, heat preservation of the sample can promote the formation of the intermetallic compounds in the diffusion layer and the growth of the diffusion layer. After heat preservation treatment 30min, the diffusion layer can achieve 300μm, meanwhile the microhardness is over 650HV. The results show that a metallurgical combination is achieved between ZL102 and high-temperature steel via this casting process, which contributes to the foundation of producing Al/steel bimetal composite materials.

Keywords: Compound casting, hot-dipping, metallurgical combination, intermetallic compounds.

1. Introduction

Aluminum alloys and steel have the irreplaceable advantages in engineering applications [1]. However, one of these alloys is difficult to meet the practical requirements in some special industrial cases. Constituted by aluminum and steel sections, the Al/steel bimetallic with the excellent performances can meet the needs for high strength and reduce weight to improve fuel economy and reduce emissions. It can effectively comply with the requirements of engineering applications, especially in the automotive industry [2].

Preparation technology of Al/steel bimetallic composites mainly includes friction stirs welding [3], squeeze casting [4] and compound casting [5], and so on. Due to the low cost and simple process, composite casting process is one of the most ideal Al/steel bimetal composite material preparation processes and it can avoid the lack of welding process. The key of composite casting process for preparing Al/steel bimetallic composites is to creat a good metallurgical bonding between the aluminum alloy and the steel substrate. Therefore, the steel substrate with a good wettability is crucial. In order to improve the wettability of the steel substrate, the pretreatment process of coating an intermediate layer on the surface of the base material has been widely adopted. Viala J. *et al.* [5] using of Al-Fin process and gravity casting to manufacture aluminum/cast iron bimetallic composites. The Al and iron can be achieved metallurgy bonding by this process, and a continuous phase layer composed of three intermetallic compounds η(Al_5Fe_2), τ_5($Al_{7.4}Fe_2Si$) and τ_6($Al_{4.5}FeSi$) is found at the interface. Bouche K. *et al.* [6] researched the formation and growth kinetics of the intermetallic compound layer, after the ferrite sample hot-dipping in Al melt at 700-900 °C. The interfacial interlayer mainly consists of Al_5Fe_2 phase and Al_3Fe phase.

In this experiment, the Al-Fin process is applied to promote the metallurgical effective combination between aluminum and steel. The solid heat-resisting steel plate is dipped into liquid aluminum and then liquid aluminum of 760 °C is cast around it through the casting mould. After casting, sample heat treatment with different time at 700 °C. The effects of different heat treatment on the interfacial microstructures and intermetallic phases at the interface between the aluminum and the steel were studied, and bonding properties of Fe/Al bimetallic interface were also discussed.

2. Experimental

2.1. The Experimental Materials

In this study, the heat-resisting steel plates of 70mm×60mm×7mm and ZL102 aluminum alloy were used as the substrate material and whose chemical compositions are respectively listed in Table 1.

Table 1. Composition in wt.% of the Heat-Resisting Steel and the ZL102

alloy	Chemical composition (wt.%)														
	C	Si	Mn	P	S	Ni	Cr	W	V	Mo	Ti	Co	Al	Nb	Fe
heat-resisting steel	0.20	0.30	0.71	0.010	0.003	0.51	10.41	0.08	0.48	0.99	<0.01	0.01	<0.01	0.17	Bal.
ZL102	-	10-13	-	-	-	-	-	-	-	-	-	-	Bal.	-	-

2.2. The Experimental Process

The presence of an impurity or oxide film on the surface of the steel substrate suppresses the diffusion of atoms during casting, resulting in greatly reduced wettability of the steel substrate [7]. In order to make a good combination between steel and aluminum, it is essential to ensure the surface of the steel plate is clean and free of oxide film [8], [9].

The experimental process is divided into three successive steps. The first step is hot-dip aluminizing. The cleaned steel plate was immersed into the ammonium chloride solution at 80 °C for 2min; and then the steel plates were dried and preheated to 250 °C. Afterwards, the steel plate was immersed into molten metal of ZL102 at 780 °C for 15min. The second step is casting. The hot aluminized steel plate was immediately placed in a graphite preheated at 400 °C and the fresh liquid ZL102 was poured into the mold. The third step is heat preservation treatment. The samples were heat preservation treatment at different time. The sample 1 had no treatment. The sample 2 and the sample 3 were respectively treated with 15min and 30min for heat preservation. Then three groups of samples are slowly cooled to room temperature.

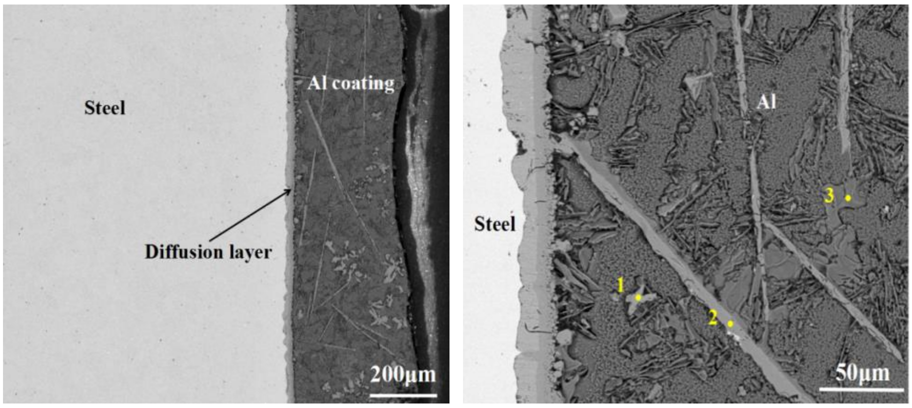
The interfacial microstructure and elements composition of the Al/steel bimetallic samples were analysed by means of scanning electron microscope (SEM), chemical composition analysis and microhardness measurement after the samples were cut, grinded, polished and corroded. And the effects of different heat treatment on the bonding properties of Fe/Al bimetallic interface were studied.

3. Results and Discussion

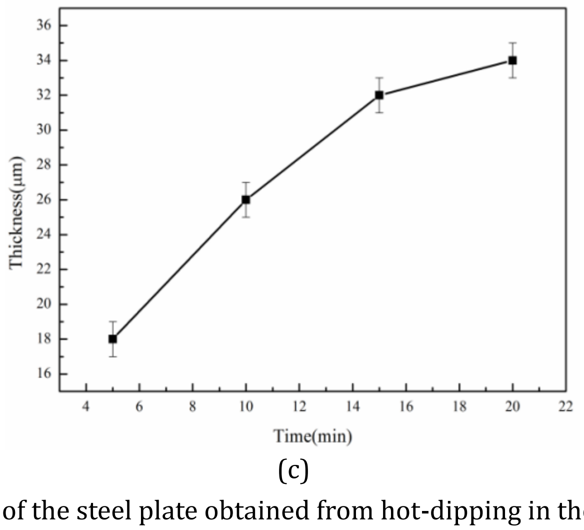
3.1. Growth and Microstructure of the Hot-Dip Al Coating

Before casting, hot-dipping Al alloys on the surface of steel can improve the wettability of the steel substrate and promote the good metallurgical bonding between steel and aluminum [10], [11]. Therefore, to analyse the microstructure and growth of aluminum coating by hot-dipping is crucial. In this experiment, the effect of different hot dipping time (5min, 10min, 15min, 20min) on the Al coating at 760 °C was studied.

It is found that there is a gap between the Al coating and the steel matrix when the hot-dipping time is 5min and 10min at 760 °C. When the hot-dipping time attains to 20min, the steel plate begins to melt obviously. And when the hot-dipping time is 15min the quality of the coating is the best. Fig1 shows the SEM image of the steel plate after hot-dipping at 760 °C for 15min and the function relationship between the hot-dip time and the thickness of the hot-dip aluminized diffusion layer. It can be seen from Fig. 1(a) that it will be obtained a three-layer structure with steel plate-transition layer-aluminum coating after 15min hot-dip coating. The steel plate and the aluminum coating are connected together through the intermediate diffusion layer, and the diffusion layer is about 32μm. The steel plate and the diffusion layer are not smooth, which is due to partial melting of the steel plate during the hot-dip plating. As can be clearly seen in Fig. 1(b), there are some strip and small block structure in the aluminum coating, which was identified using spot scanning of SEM, as shown in Table 2. As can be seen from the Fig. 1(c) that the thickness of the diffusion layer increases with the increase of the hot-dipplating time, but the speed of growth gradually slows down. When the thickness of the diffusion layer reaches 32μm, it tends to stabilize. It is presumed that when the hot dip coating reaches a certain time, the thickness of the diffusion layer will not increase any more.



(a) (b)



(c)

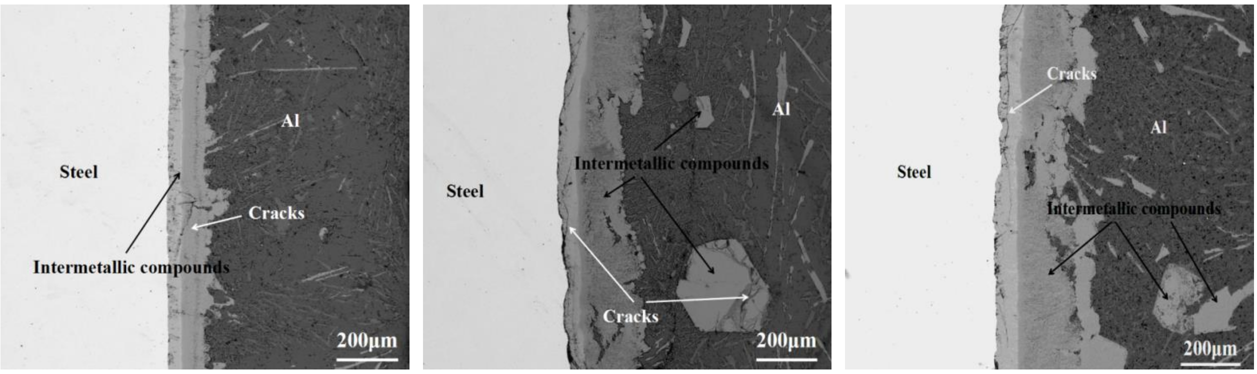
Fig. 1. (a), (b) SEM image of the steel plate obtained from hot-dipping in the Al alloy; (c) the function relationship between the hot-dipping time and the thickness of the diffusion layer.

Table 2. Results of the Chemical Analysis from the Selected Regions in Fig. 2(b)

	Composition (at.%)						
	Al	Si	Mo	V	Cr	Mn	Fe
1	74.29	11.77	0.34	0.42	2.13	0.67	10.35
2	68.36	20.66	0.08	0.22	0.73	0.36	9.58
3	68.40	24.79	0.24	0	0.46	0	6.10

3.2. Microstructures and Compositions of the Al/Steel Interfaces after Pouring

Fig. 2 is the optical micrograph of the Al/steel interface from the 3 groups casting samples. Fig. 2(a) presents the interface microstructure of sample 1. As can be seen, a continuous diffusion layer with a thickness of 150μm is achieved in the interface region, which connects the steel plate with the aluminum alloy. The interface with the iron substrate is relatively flat, while the interface with the aluminum substrate has much prominence. The contact interface between the diffusion layer and the steel is relatively flat, while the contact interface between the diffusion layer and the aluminum is relatively rough. And there are some strip and small block structures in the aluminum matrix adjacent to the diffusion layer. It is shown from the diagram that the diffusion layer after 15min heat preservation treatment is about 210μm, and treated with 30min the diffusion layer is more than 300μm. It can be clearly found that as the heat preservation treatment time increases, the thickness of the diffusion layer gradually increases, and the contact interface becomes no longer smooth and some strip and small block structures appear in the aluminum substrate adjacent to the diffusion layer. Due to after the heat treatment, the surface of the steel has melted and more steel has diffused into the aluminum matrix, forming intermetallic compounds during the cooling process. Furthermore, it can be seen from Fig. 2 that there are some micro-cracks in the diffusion layer, because the physical and chemical properties of aluminum and steel are quite different, and microcracks are easily initiated during the cooling process.



(a) (b) (c)

Fig. 2. Optical micrographs of interfacial microstructures of the Al/steel bimetallic composites: (a) without heat preservation; (b) heat preservation 15min; (c) heat preservation 30min.

In order to study the effect of heat treatment on the interface element concentration trends, the sample 1 and the sample 3 have been tested and analysed by line scanning and point scanning, and the results of the analysis are shown in Fig. 3. From Fig. 3(b) and (d), we can see that the two elements of Fe and Al have taken inter-diffusion. Nearby steel side of the atomic ratio about Fe:Al is close to 1:3, and then gradually decreases. Compared with Fig. 3(b) and (d), we can find that the thickness of diffusion layer increases obviously after heat treatment, due to heat preservation has promoted the diffusion of atoms and increased the thickness of the diffusion layer. In addition, the point scanning positions are shown in Fig. 3(a) and (c). And the results of the analysis are shown in Table 2. Combined with the analysis results of point scanning and the microstructure, it can be found that the middle layer is mainly composed of $Al_{4.5}SiFe$ phase, and there are some strip and small block $Al_{4.5}SiFe$ phases in the aluminum matrix. The growth of the interface organization process can be inferred as: after hot dipping aluminum, the steel plate surface obtained a thin layer of aluminum coating; During the process of casting, liquid aluminum and aluminized layer contact quickly, and break through the oxide layer of the surface of the aluminum layer. After the heat treatment, the liquid aluminum and the steel plate undergo the metallurgical reaction to obtain $Al_{4.5}SiFe$ diffusion layer and a part of Fe atom diffuse into aluminum liquid and then obtain discontinuous $Al_{4.5}SiFe$ phase.

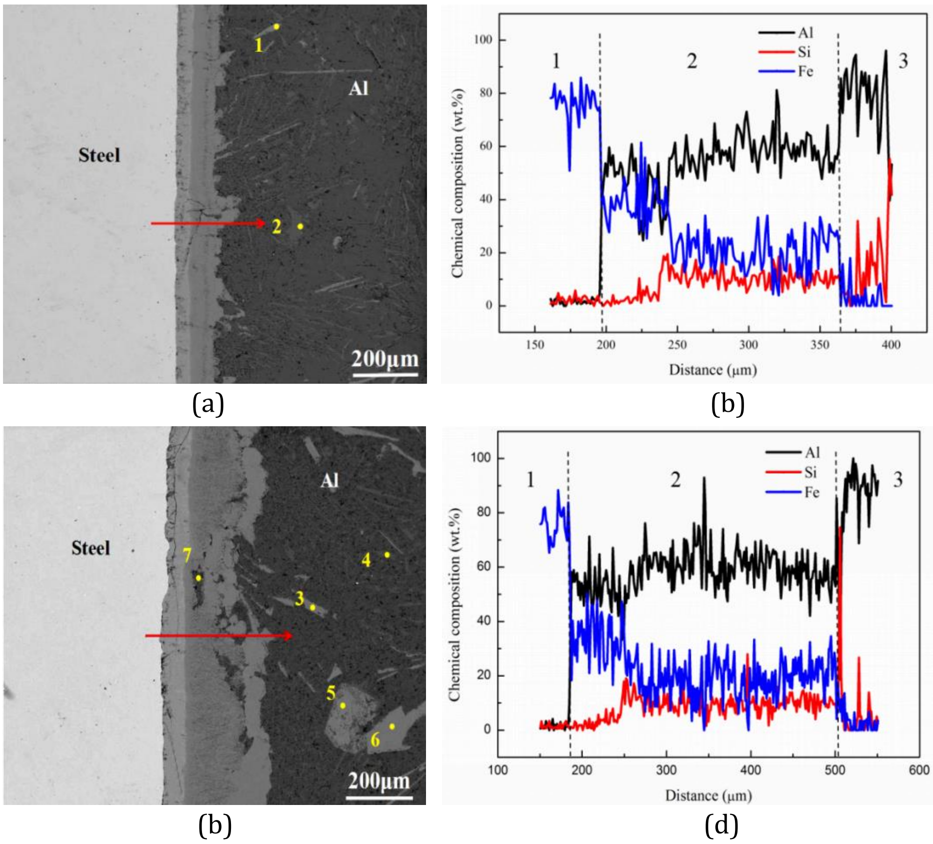


Fig. 3. SEM images of the bonding interface and the analysis of linear scanning: (a) without heat preservation; (b) the analysis of (a); (c) heat preservtion30min; (d) the analysis of (c).

Table 3. Results of the Chemical Analysis from the Selected Regions in Fig. 3(a) and (c).

	Composition (at.%)							Phase
	Al	Si	Mo	V	Cr	Mn	Fe	
1	66.29	16.31	0.19	0.48	0.44	0.47	15.83	$Al_{4.5}SiFe$
2	3.12	96.16	0.27	0.26	0	0.19	0	Si
3	66.92	16.33	0.26	0.32	0.38	0.54	15.25	$Al_{4.5}SiFe$
4	1.65	97.34	0.33	0.26	0.10	0	0.32	Si
5	71.95	9.53	0.34	0.64	2.88	0.82	13.85	Al_5FeSi
6	67.99	15.93	0.36	0.25	0.36	0.54	14.57	$Al_{4.5}SiFe$
7	96.95	1.16	0.42	0.18	0.26	0	1.04	Al

Fig 4 is the X-ray diffraction (XRD) analysis of the steel and aluminum composite interface. It can be seen from the diagram that the main diffraction peaks at the interface are Fe and Al, and a little of Si. It can be speculated that during the composite process Al and Fe had obvious interdiffusion. The main intermetallic compound [12] at the interface is $Al_{4.5}FeSi$, which is consistent with point scanning analysis results.

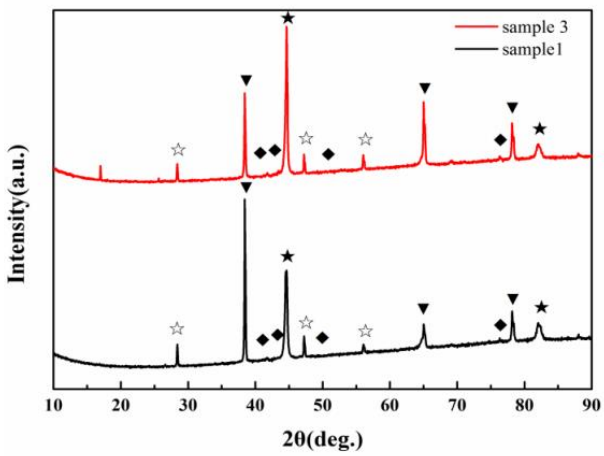


Fig. 4. XRD spectra of the Al/steel bimetallic composites (▼-Al peaks, ☆-Si peacks, ◆-$Al_{4.5}$FeSi peaks,★-Fe peacks)

3.3. Microhardnesses of the Al/Steel Interfaces after Pouring

The microhardnesses of the sample 1 and sample 3 are shown in Fig. 5. The changes of microhardness are clearly seen from the figure. According to the microhardness value, it can be divided into three hardness ranges. The microhardness of aluminum matrix is about 50HV, and the steel matrix is about 250HV. The microhardness of the diffusion layer is much higher than that of matrix metal, and the microhardness of the diffusion layer in sample 3 can reach 650HV. This is due to the formation of the higher hardness aluminum-iron intermetallic compound in the diffusion layer, thereby increasing its microhardness. The microhardness on the side of the steel substrate of sample 3 is lower than that of sample 1, because the slow cooling after the heat preservation treatment is equivalent to the annealing for the steel substrate.

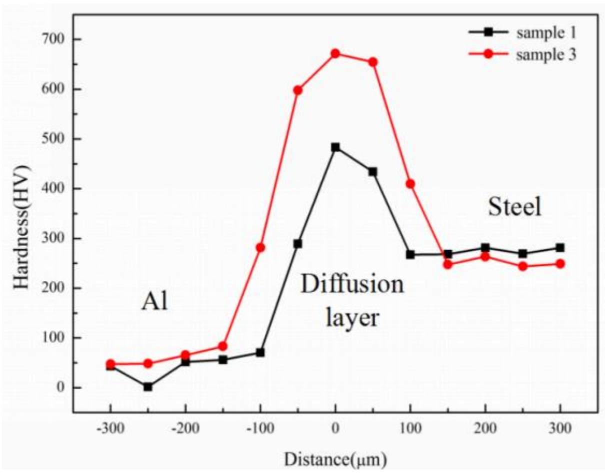


Fig. 5. Microhardnesses of the interfaces of the Al/steel bimetallic composites.

4. Conclusion

(1) Hot-dipping Al coating can improve the wettability of the surface of the steel substrate. It promotes the formation of a good metallurgical bonding layer at the interface between the steel substrate and Al alloy. When the steel plate is hot dipped at 760 °C for 15min, a uniform and compact aluminum coating can be formed on the surface of the steel plate and a 32μm thick diffusion was formed between the steel plate and

the aluminum coating.

(2) Al/steel bimetal composite can be prepared by composite casting after hot-dip treatment. The hot-dip Al treatment promotes the liquid-solid reaction between Al alloy and steel during the casting process, so that the $Al_{4.5}SiFe$ were formed in the diffusion layer.

(3) The existence of a large number of intermetallic compounds in the diffusion layer making the microhardness of the diffusion layer is much higher than the base metal. In addition, heat preservation of the sample can promote the formation of the intermetallic compounds in the diffusion layer and the increase of the thickness in the diffusion layer.

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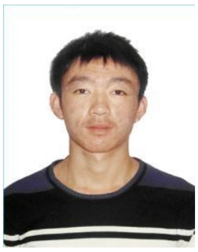

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