Arch. Metall. Mater. **64** (2019), 3, 889-892

DOI: 10.24425/amm.2019.129467

HYO-JUNG KIM*,**, TAE HYEONG KIM*, JE SIK SHIN*, SEUNG YEON PARK*,
SOONGKEUN HYUN**, KYONG MOOK LIM*#

EFFECT OF SURFACE TREATMENTS ON CAST-BONDING CHARACTERISTICS OF STEEL-ALUMINUM HYBRID COMPOSITE MATERIALS

In this study, we investigated the bonding mechanism of surface-treated steel with an Al-Si alloy in order to produce steel-aluminum (STL-Al) hybrid composite materials by cast-bonding. The results showed that there are differences in the phase and properties of the hybrid composite materials bonded specimens depending on the surface treatment of the steel sheet used, and that the bonding conditions can be controlled further by detailed conditions of the surface treatment. Based on the interfacial bonding strengths measured here, the galvanized surface treatment induced metallurgical bonding to form a reaction layer on the bonding surface and was determined to be the most effective surface treatment.

Keywords: Cast-bonding, Aluminum, Steel sheet, Composite material, Bonding surface

1. Introduction

The automobile industry is currently focused on improving automobiles' safety of passengers and fuel efficiency. In response to this, research focusing on materials that can improve both safety and fuel efficiency is actively underway [1,2], and attention is focused on hybrid composite materials that can satisfy them [3]. In this study, steel-aluminum (STL-Al) hybrid composite materials that are both strong and light weight have been tested and a pathway to creation of STL-Al hybrid composite materials with different bonding properties has been suggested.

The STL-Al hybrid composite materials used in this study were manufactured by high-pressure die-casting instead of cladding, welding, etc. High-pressure die-casting allows for bonding at the same time as casting, thus ensuring economic efficiency and productivity. Each steel sheet used in this study had one of four specific surface treatments that can be roughly divided into three types (see Table 1): galvanized surface treatment, galvannealed surface treatment, and Zn thermal spray coating. Two conditions were tested for the galvanized surface treatment, to investigate the effect of different Zn plating thickness on the bonding properties.

Bonding of composite materials can be by metallurgical and mechanical bonding. In metallurgical bonding, intermetallic compounds are formed generally. These intermetallic compounds are very brittle at room temperature so that are major factor in fracture. Therefore, it is necessary to control intermetallic compounds [4,5]. We studied metallurgical bonding by observing formation and behavior of intermetallic compounds in high-pressure die-casting and each surface treatment condition.

TABLE 1

Surface treatments of steel sheets used in the experiment

Surface treatment	Galvanized Surface treatment		Galvannealed Surface treatment	Zinc Thermal Spraying
Steel grade	590DP			
Size	50 * 40 mm			
Detailed condition	Zn plating; 10 μm	Zn plating; 100 μm	Fe-Zn plating; 10 μm	Fe-Zn plating; 100 μm
Numbering	#1	#2	#3	#4

2. Experimental

Each steel sheet had one of the four specific surface treatments described in the following table and subsequently underwent cast-bonding with an Al-Si alloy (Silafont-36).

The cross-sectional microstructure of the steel sheet from each surface treatment is shown in Fig. 1. Fig. 1(a) and (b) each show a flat Zn-plated layer, approximately 10 μm and 100 μm thick respectively. Fig. 1(c) shows the Fe-Zn intermetallic compound layer after alloying by heat treatment [6], and Fig. 1(d) shows the rough coating formed by the Zn bead layer.

* KOREA INSTITUTE OF INDUSTRIAL TECHNOLOGY, KOREA INSTITUTE FOR RARE METAL, 12 GAETBEOL RD., YEONSU-GU, INCHEON, 21999, KOREA
** INHA UNIVERSITY, INCHEON, KOREA
# Corresponding author: mook@kitech.re.kr

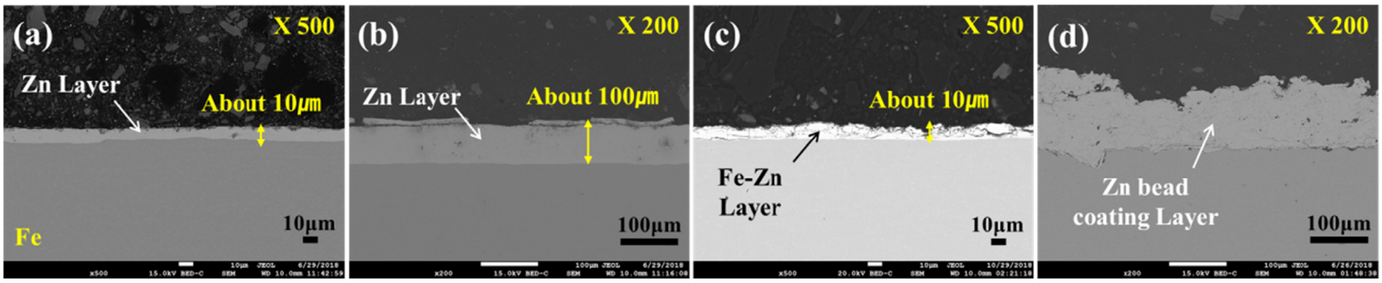


Fig. 1. Cross-sectional SEM micrograph of each surface-treated steel; (a) Galvanized steel-10 μm (#1), (b) Galvanized steel-100 μm (#2), (c) Galvannealed steel (#3), (d) Zn thermal spray coating (#4)

For cast-bonding, a lab-scale high-pressure die-casting system was constructed with an injection speed of 30 m/s. In the cast-bonding process, a steel sheet was inserted into the mold and the Al-Si alloy (Silafont-36) was injected at 720°C to produce the bonded specimen. Table 2 shows the overall substance of the experiment.

In order to investigate the bonding characteristics of each surface treatment, the interface microstructure and interfacial bonding strength were analyzed. The interface microstructure was observed by field emission scanning electron microscopy (FE-SEM) and analysis of the bonded specimen was carried out by energy dispersive X-ray spectrometry (EDS) point analysis and mapping. (FE-SEM and EDS ; JEOL KOREA, JSM-7100F). The interfacial bonding strength was measured using tensile tester. The specimens were produced in accordance with ASTM D1002 and the bonding area was 300 mm^2. Fig. 2 shows schematic diagram of the tensile test specimens and tester.

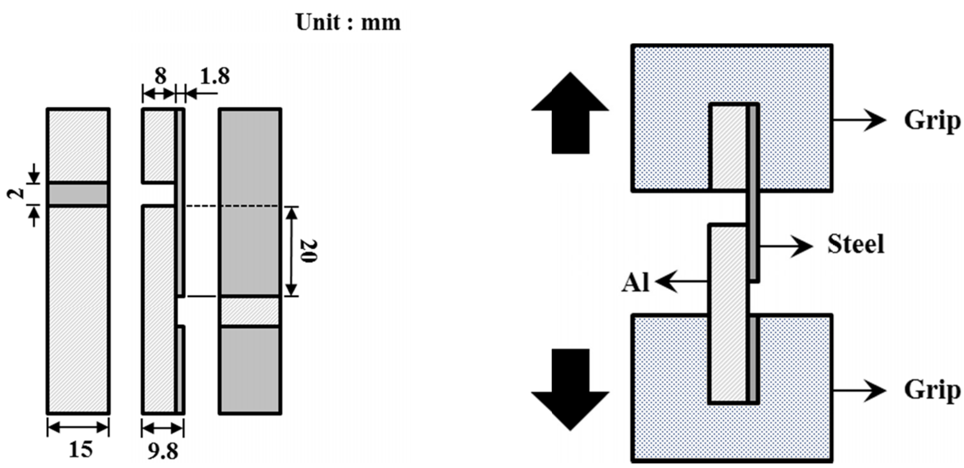
TABLE 2

Overall substance of experiment

Alloy	Silafont-36 (9Si-0.5Mn-0.38Mg-0.1Ti-0.02Sr)					
Pouring Temperature	720°C					
Mold Pre-heating	**Sleeve**	200°C	**Moving plate**	200°C	**Fixed plate**	200°C
Injection Speed	Rod 6 m/s → Gate 30 m/s					
Steel sheet	590 DP 1.8t					
	50 * 40 mm Size					
Injection Pressure	150 Bar					

3. Results and discussion

Fig. 3 shows the cross-sectional microstructure of the bonded specimen for each surface-treated steel : #1 and #2 were well-bonded, #3 was not bonded, and #4 displayed poor bonding due to fractures that occurred during processing. As shown in Fig. 3(a) and (b), reaction layers [7] were formed at the STL-Al interface of #1 and #2 and bonding was successful. Fig. 3(a) and (b) also show that the shape of the reaction layer is different under the two conditions as #1 formed a flat, thin reaction layer with an average thickness of approximately 1 μm, whereas the reaction layer on #2 is considerably thicker and formed from several mixed phases. In Fig. 3(c), #3 is shown to be fractured over the entire interface and did not bond, while in Fig. 3(d), #4 was mostly fractured but may have partially bonded due to the roughness of the surface.



(a) (b)

Fig. 2. Schematic diagram of the tensile test specimens and tester; ASTM D1002; (a) Schematic diagram of tensile test specimen, (b) Schematic diagram of tensile tester

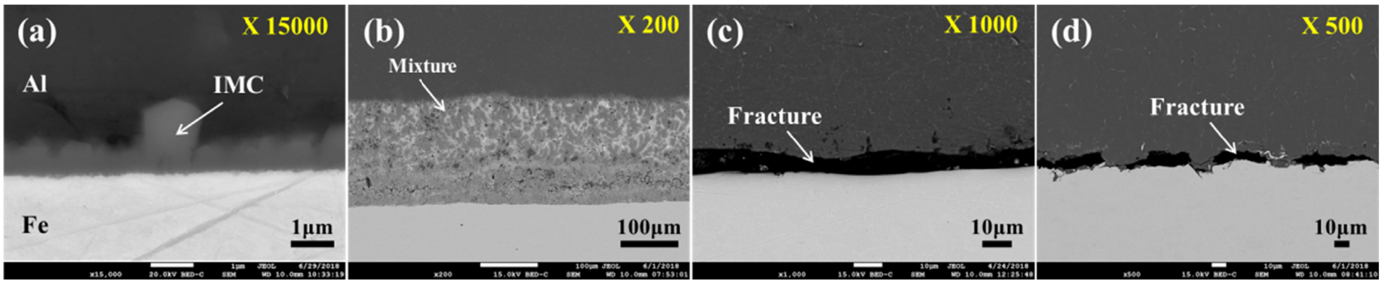


Fig. 3. Cross-sectional SEM micrograph of the bonded specimen for each surface-treated steel; (a) Galvanized steel-10 µm (#1), (b) Galvanized steel-100 µm (#2), (c) Galvannealed steel (#3), (d) Zn thermal spray coating (#4)

Fig. 4 shows the interfacial bonding strength of the bonded specimen for each surface treated steel. The interfacial bonding strength was the highest on #1 at approximately 35 MPa, followed closely by #2 at 30 MPa. Samples #3 and #4 both failed to bond, measuring less than 1 MPa for interfacial bonding strength, which supports the observation from Fig. 3(c) and (d). In previous studies, gravity casting was used, but in this experiment, high-pressure die-casting was used, so the difference in interfacial bonding strength was shown [8].

The high interfacial bonding strength of #1 and #2 is considered to be the result of the reaction layer generated at the STL-Al interface; therefore, EDS mapping and point analysis was performed to probe the interface (Fig. 5, Fig. 6 and Table 3). In #1, the Zn plating layer, initially 10 µm thick, melted into the Al matrix. Hence, the reaction layer is mixture of the Al-Si alloy (Silafont-36) and the underlying steel: Al, Si and Fe. In the case of #2, the 100 µm Zn-plated layer did not melt completely into Al matrix, resulting in a reaction layer formed from several phases of Al, Si, Zn and Fe, which is shown by EDS analysis in Fig. 5, Fig. 6 and Table 3.

Based on the result of the EDS point analysis, the phase was identified [9,10]. Sample #1 was identified as intermetallic compounds $FeAl_3$ and τ_5-Fe_2Al_7Si and Sample #2 was identified as a mixture of several phases of Al, Si, Zn and Fe. In both #1 and #2, the Zn plating layer melted into the Al matrix and reacted with the Al to form the reaction layer at the STL-Al interface. In the case of the fractured specimens, the Fe-Zn intermetallic compound layer from the alloying process of #3 is thought to disturb the formation of a reaction layer and in #4, the Zn

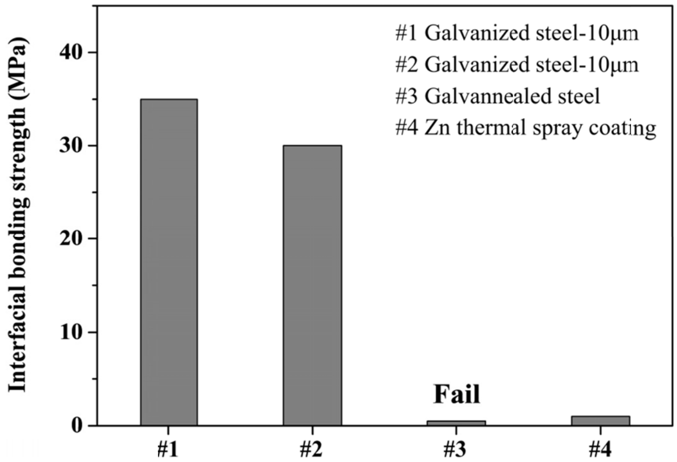


Fig. 4. Interfacial bonding strength of the bonded specimen for each surface treated steel

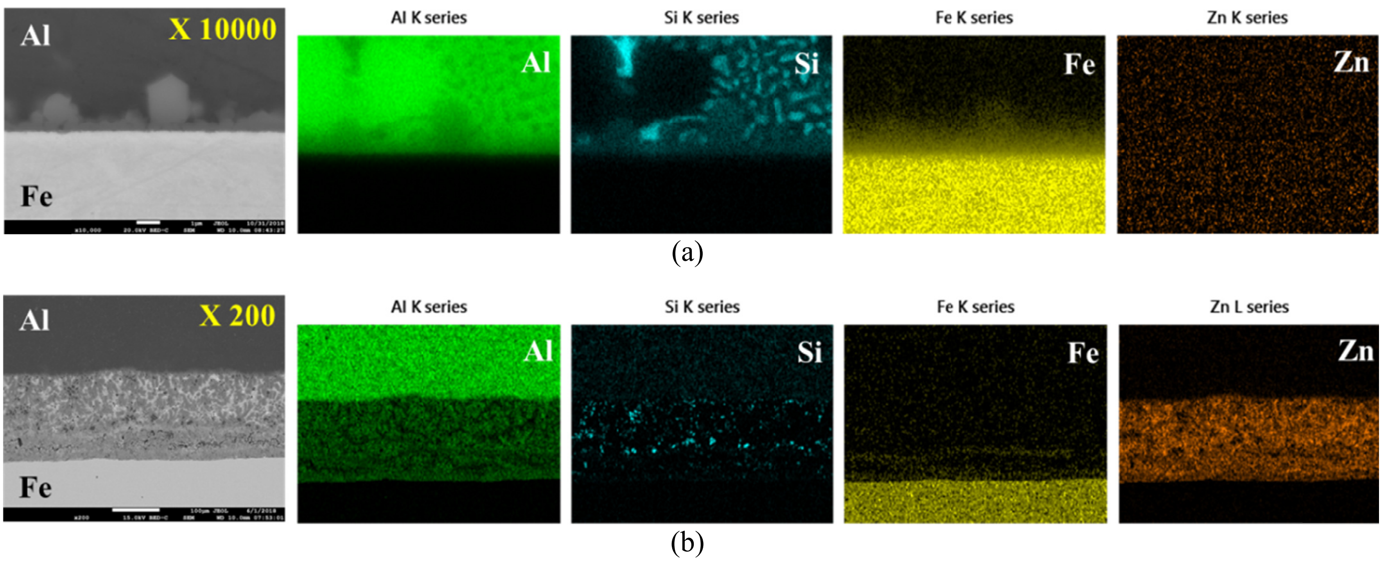


Fig. 5. Mapping analysis of the bonded specimen's reaction layer under galvanized surface treatment conditions; (a) Galvanized steel-10 µm (#1), (b) Galvanized steel-100 µm (#2)

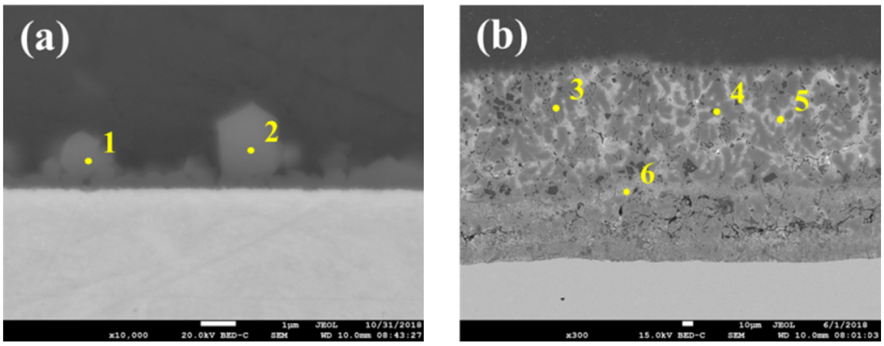


Fig. 6. EDS point analysis of the bonded specimen's reaction layer under galvanized surface treatment conditions; (a) Galvanized steel-10 µm (#1), (b) Galvanized steel-100 µm (#2)

TABLE 3

EDS point analysis of the bonded specimen's reaction layer (Ref. Fig. 6)

No.	Element Compositions			wt.% / at.%
	Al	Si	Fe	
1	58.42	10.97	30.61	
	69.6	12.6	17.8	
2	57.96	10.51	31.53	
	68.98	12.19	18.83	
	Al	Si	Fe	Zn
3	72.46	—	—	27.54
	86.44	—	—	13.56
4	7.89	85.54	—	6.56
	8.51	88.57	—	2.92
5	32.22	—	—	67.78
	53.53	—	—	46.47
6	46.86	2.1	6.71	44.33
	65.59	2.82	5.98	25.61

thermal spray coating layer was separated by the difference in thermal expansion coefficient between the steel and the coating layer, so that oxidation occurred and there was no reaction layer. However, due to the rough surface of steel on #4, the Al-Si alloy (Silafont-36) was able to fill in the roughness on the surface and create a weak bond measured as less than 1 MPa.

It is remarkable that the shape and bonding characteristics of the reaction layer vary depending on the Zn plating thickness of galvanized steel; this indicates that control of bonding properties is possible through detailed control of the surface treatment condition. Especially, the intermetallic compound has high brittleness at room temperature and it needs to be controlled, but it is formed thin and flat at less than 1 µm in the high-pressure die-casting environment where the cooling rate is fast as in this experiment, the bonding strength is improved.

4. Conclusions

In this study, the bonding properties of STL-Al hybrid composite materials prepared from steel sheets with different surface treatments were investigated. All three of the surface treatments tested here used Zn, yet the bonding characteristics differed depending on the method. Of the three surface treatments, galvanized steel succeeded in forming a reaction layer that promotes good bonding, while both galvannealed and thermal spray coated steel were found to be unsuitable for bonding. Under galvanized surface treatment conditions, the reaction layer of galvanized steel with a 10 µm-think Zn layer (#1) formed an intermetallic compounds and exhibited the highest bonding strength. Galvanized steel with a 100 µm-thick Zn layer (#2) formed a reaction layer that was a mixture of various phases and displayed similarly good bonding strength. These results indicate that a bonding mechanism that creates reaction layer at the interface is an effective mechanism for cast-bonding and that the bonding properties of materials created by this method can be controlled by controlling details of the surface treatment, such as the Zn plating thickness of galvanized steel.

REFERENCES

[1] L.Y. Sheng, CompositesPart B: Engineering **42**, 6, 1468-1473 (2011).

[2] A. Bouayad, JARME **1**, 4, 226-231 (2010).

[3] H. Springer, Materials Science and Engineering A **528**, 1-2, 4630-4642 (2011).

[4] Wei-Jen Cheng, Intermetallics **19**, 10, 1455-1460 (2011).

[5] F.A. Calvo, Journal of Materials Science **23**, 2273-2280 (1988).

[6] Jun-Kai Chang, Metallurgical and Materials Transactions A **49**, 8, 3715-3728, (2018).

[7] S. Kobayashi, Materials Science and Engineering A **338** (2002).

[8] W. Jiang, Journal of Alloys and Compounds 742-751 (2016).

[9] S.M. Kang, K S. Han, D.G. Kim, ISIJ International **52**, 7, 1342-1347 (2012).

[10] W. Fragner, B. Zberg, R. Sonnleitner, P. Uggowitzer, Materials Science Forum, **519-521**, 1157-1162 (2006).