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Original article

# Interfacial Microstructure of Dissimilar Weld of Steel to Aluminum Containing Intermediate Metals and its Effect on Mechanical Properties

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**Abstract:** Dissimilar welding of aluminum alloy to steel is a key technology for weight reduction in car body structures. However, brittle intermetallic compounds (IMC) layer is formed at the weld interface, decreasing the weld strength. In this study, dissimilar welding of aluminum alloy 5052 to interstitial free steel with Al–Zn filler materials and Ni plating was performed by gas tungsten arc welding, and the effect of these intermediate metals on the mechanical properties and interfacial microstructures of the welds was examined. Simultaneous addition of Zn and Ni drastically improved the tensile shear strength of the welds from 41 MPa to 120 MPa. Microstructural analysis revealed that the addition of Zn and Ni reduced the IMC thickness. Nanoindentation measurements showed that Zn addition reduced the IMC hardness, and the subsequent addition of Ni with Zn further decreased the IMC hardness. This reduction of the IMC hardness, as well as the reduction of the IMC thickness, might contribute to the drastic improvement of the tensile shear strength of the welds.

**Keywords:** Dissimilar welding; Weld strength; Microstructure; Intermetallic compound; Nanoindentation

## 1. Introduction

Multi-material structures combining aluminum (Al) alloy to steel can be used for car body structures for weight reduction, energy conservation and global emission reduction [1,2]. However, dissimilar welding of Al alloy to steel is still challenging because of the formation of the brittle intermetallic compound (IMC) at the weld interface [3,4]. Therefore, it is important to understand the formation mechanism of IMCs at Al/steel dissimilar weld interface and to control their microstructures in order to achieve a reliable welding of Al alloy to steel.

Addition of an intermediate metal is one of the approaches to modify the microstructures of the IMC at the dissimilar weld interface because the intermediate metal changes the interfacial reaction during dissimilar welding. Effect of Zn addition on the dissimilar welding of Al alloy to steel has been paid attention because Zn has been widely used as a coating material on steel sheets. It is generally accepted that Zn addition results in a decrease in the hardness of the IMC layer, which contributes to

the improvement of the Al/steel weld strength [5–7].

Recently, simultaneous addition of multiple intermediate metals is found to improve the strength of dissimilar welds more than the single addition of each intermediate metal. The authors [8] reported that the simultaneous addition of Ni and Si, which results in the refinement of  $\eta$ -Fe<sub>2</sub>Al<sub>5</sub> grains and the reduction of the IMC thickness, respectively, successfully improved the weld strength of AA1050/Fe welds by combining the positive effects of these intermediate metals. This study clearly showed a possibility for further improvement of the Al/steel weld strength by the simultaneous addition of multiple intermediate metals.

In this study, therefore, the effect of the simultaneous addition of Zn and Ni on the weld strength and microstructure of IMC of the Al/steel welds was studied.

## 2. Experimental procedures

### 2.1. Materials and welding

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Gas tungsten arc welding (GTAW) was used for welding of AA5052 sheets to interstitial free (IF) steel sheets with Al–X at.% Zn (X = 0, 1, 3, and 5) filler materials. The sheets had the same thickness of 2 mm, and these chemical compositions are presented in Tables 1 and 2, respectively. In order to study the effect of Ni on the Al/steel dissimilar welding, Ni plating, approximately 20 μm in thickness, was electroplated on the IF steel sheets prior to welding. Al–X at.% Zn (X = 0, 1, 3, and 5) filler materials were prepared by casting of a molten Al alloy produced from a pure Al (99.8%) ingot and pure Zn (99%) powder. The Al–Zn cast alloys were rolled to 2 mm in thickness, followed by cut into bars with dimensions of 100 × 5 × 2 mm<sup>3</sup>.

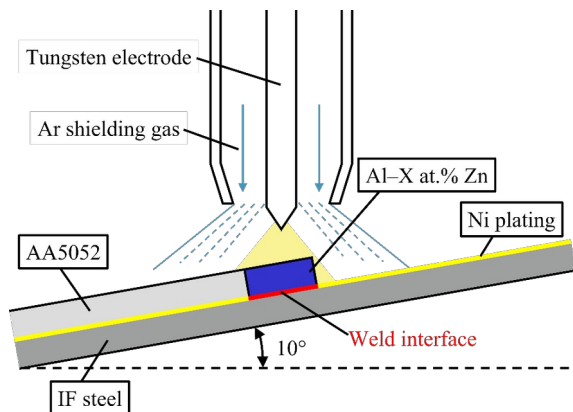
**Table 1** Chemical composition of IF steel (wt.%).

Fe	C	Si	Mn	P	S
Bal.	0.003	<0.000	0.35	0.020	0.008

**Table 2** Chemical composition of AA5052 (wt.%).

Al	Si	Fe	Cu	Mn	Mg	Cr	Zn
Bal.	0.08	0.25	0.01	0.01	2.61	0.17	0.02

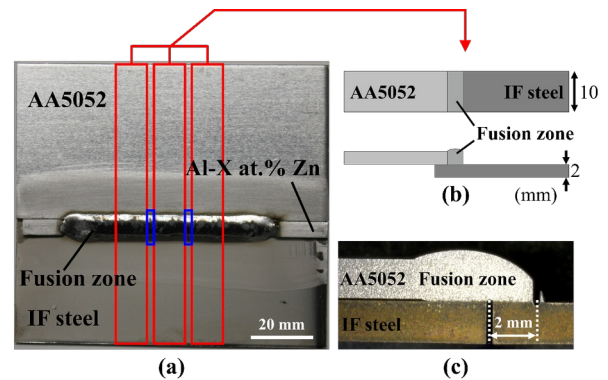
Figure 1 shows a sketch of the GTAW process. Prior to welding, the surfaces of an AA5052 sheet and an Al–Zn filler bar were ground with a 400-grit SiC paper to remove the oxide layer and subsequently cleaned with ethanol. To improve the weldability, a flux was placed on the steel surface. An AA5052 sheet and a filler bar were set on an IF steel with an overlap width of 25 mm. The GTAW parameters included a welding current of 140 A, an arc voltage of 9 V, a welding speed of 200 mm/min, an arc length of 1 mm, and tilting angle of 10° from the horizontal. Argon shielding gas with 20 L/min flow rate was used during welding to avoid the oxidation of the weld.



**Figure 1** Sketch of GTAW process.

## 2.2. Mechanical and microstructural tests

The weld strength of the Al/steel dissimilar welds was examined by tensile shear testing. For each weld, three specimens were cut from the center part of the welded sample perpendicular to the welding direction, as indicated by red rectangles in Figure 2 (a). The dimensions of the test specimens are provided in Figure 2 (b). Two slits were introduced at the top and the bottom of the test specimen by wire electrical discharge machining, as shown in Figure 2 (c). The aims of the insertion of these slits were (1) to standardize the interfacial test area at 2 × 10 mm<sup>2</sup>, (2) to eliminate the effect of the shape of the Al fusion zone on the weld strength, and (3) to suppress the fracture in the Al base material during the test. Tensile shear tests were performed on a screw-driven testing machine at a crosshead speed of 0.3 mm/s at room temperature.



**Figure 2** (a) Specimen location, (b) configuration of tensile test specimen, and (c) location of slits.

For microstructural analysis of the weld interface, cross sections of the welds were cut, as indicated by blue rectangles in Figure 2 (a), and then prepared through the standard metallographic sample procedure. The cross section was observed by scanning electron microscopy (SEM), and the thickness of the IMC layer formed at Al/steel weld interface was quantified in backscatter electron (BSE) mode. Distributions of intermediate metals at the Al/steel dissimilar weld interfaces were also analyzed using electron probe microanalyzer (EPMA).

X-ray diffraction (XRD) spectra were obtained from the fracture surfaces in order to identify the fracture position during the tensile shear test.

Nanoindentation was employed to study the effect of intermediate metals on the hardness of IMC layer. Using a Berkovich tip, a maximum load of 20 mN, a loading and unloading time of 20 s, and a dwell time of 5 s were applied.

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### 3. Results

#### 3.1. Tensile shear strength

Figure 3 shows the effects of the simultaneous addition of Zn and Ni on the tensile shear strength of the Al/steel weld. All specimens were fractured at the weld interface. Without any intermediate metals, tensile shear strength is 41 MPa. Noticeably, the weld strength increases with an increase in Zn content of filler up to 3 at.%, beyond which it decreases. Clearly, the subsequent addition of Ni with Zn further improves the weld strength. It should be noted that the highest tensile shear strength of 120 MPa is achieved when the Al-3 at.% Zn filler and Ni plating were simultaneously used.

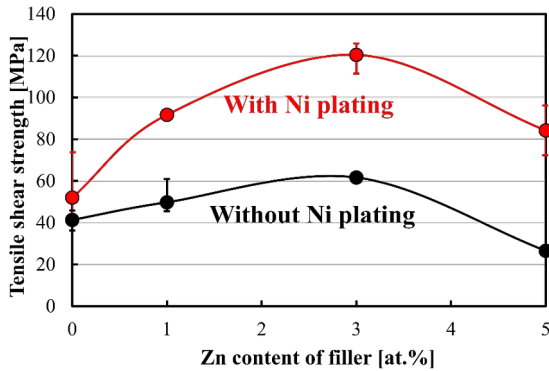


Figure 3 Effect of Zn and Ni on tensile shear strength of weld.

#### 3.2. Microstructure at the weld interface

Figure 4 (a) shows the BSE images of the different Al/steel dissimilar weld interfaces. Ni plating on IF steel was completely dissolved into the Al fusion zone, and an IMC layer formed at the interface between Al and steel, resulting from a direct contact between Al melt and steel. IMC layer at all welds exhibits similar morphology, which are often called as “tongue-like” structure [9,10]. It is noteworthy that IMC layer formed at the weld produced with Al-5 at.% Zn filler contains many defects, which might be responsible for the decrease in the tensile shear strength, as shown in Figure 3. EPMA quantitative analysis suggested that IMC layer without any intermediate metals mainly consisted of  $\eta$ -Fe<sub>2</sub>Al<sub>5</sub> layer with chemical composition of 27 at.% Fe and 73 at.% Al, which corresponds to many previous studies on the Al/steel reaction [11,12]. Figure 4 (b) shows chemical composition profiles across the weld interface produced with Al-3 at.% Zn filler. The Al and Fe profiles suggest that  $\eta$ -Fe<sub>2</sub>Al<sub>5</sub> layer (27 at.% Fe and 73 at.% Al) is also the dominant phase in the IMC layer. Zn profile clearly shows that  $\eta$ -Fe<sub>2</sub>Al<sub>5</sub> layer contains Zn between about 0.2

and 1 at.%, which suggests the formation of  $\eta$ -Fe<sub>2</sub>Al<sub>5</sub>Zn<sub>x</sub> layer by Zn addition [13,14]. Noticeably, Zn content inside  $\eta$ -Fe<sub>2</sub>Al<sub>5</sub>Zn<sub>x</sub> layer increases toward steel side, forming Zn-rich zone at  $\eta$ -Fe<sub>2</sub>Al<sub>5</sub>Zn<sub>x</sub>/steel interface. Figure 4 (c) shows chemical composition profiles across the weld interface produced with Al-3 at.% Zn filler and Ni plating. The dominant phase in the IMC layer is also  $\eta$ -Fe<sub>2</sub>Al<sub>5</sub>Zn<sub>x</sub> containing Zn between about 0.3 and 1 at.%, and the Zn-rich zone is also observed. On the other hand, Ni is not detected inside the dominant  $\eta$ -Fe<sub>2</sub>Al<sub>5</sub>Zn<sub>x</sub> layer but enriched at the Al/IMC interface, suggesting the formation of thin  $\tau_1$ -FeNiAl<sub>9</sub> layer, which was formed at the Al/steel interface containing Ni [8,15,16]. In addition to chemical composition of  $\eta$ -Fe<sub>2</sub>Al<sub>5</sub> layer, intermediate metals change the thickness of IMC layer, as presented in Figure 5. Except for the weld produced with Al-1 at.% Zn filler without Ni plating, addition of Zn and Ni plating reduces the IMC thickness. According to previous studies, it is expected that the reduction of IMC thickness could contribute to the increase in the tensile shear strength of the welds.

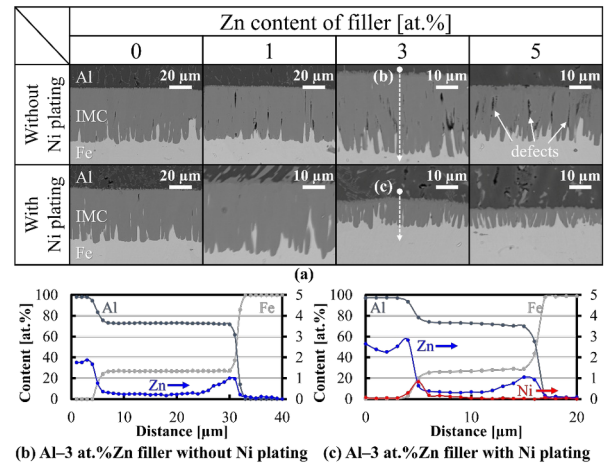


Figure 4 (a) BSE images, (b) and (c) chemical composition profiles across the Al/steel weld interface.

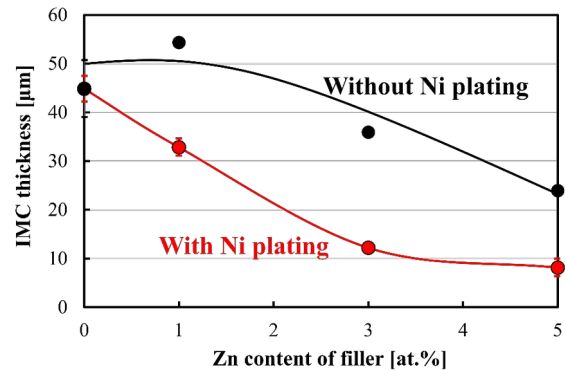
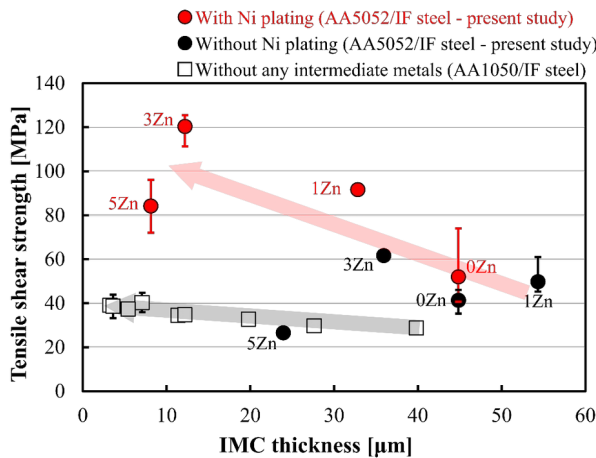


Figure 5 Effect of Zn and Ni on IMC thickness at weld interface.

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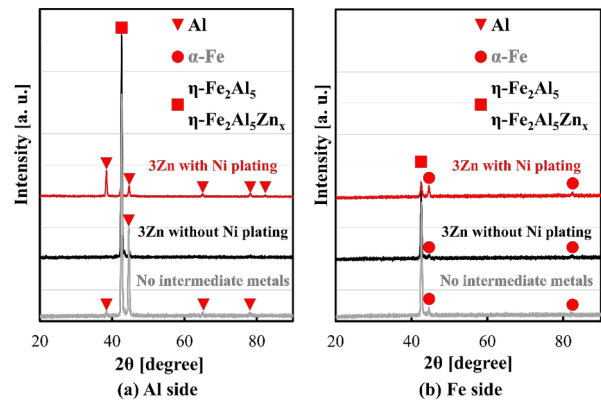
Relationship between tensile shear strength and IMC thickness of the AA5052/IF steel welds containing Ni and Zn in present study are shown in Figure 6, accompanying that of the AA1050/IF steel welds welded by GTAW without any intermediate metals from our unpublished work. It seems that tensile shear strength increases with a decrease in IMC thickness, except for those of the weld produced with Al-5 at.% Zn filler because of the presence of many defects inside IMC layer, indicated by white allows in Figure 4. This result tends to confirm the contribution of reduced IMC thickness on the improved strength in welds with Zn and Ni additions. However, in the AA1050/IF steel welds produced without any intermediate metals, the improvement of the weld strength by reducing IMC thickness is limited, which implies that the strength improvement by simultaneous addition of Zn and Ni was affected by another factor, in addition to the thickness reduction of IMC layer. Therefore, the microstructures of the weld produced with Al-3 at.% Zn filler with/without Ni plating were further studied in order to clarify the mechanism of the improvement of the weld strength by addition of these intermediate metals.



**Figure 6** Relationship between tensile shear strength and IMC thickness.

### 3.3. XRD on fracture surface

Figure 7 shows XRD spectra obtained from the fracture surfaces of the welds produced without any intermediate metals, with Al-3 at.% Zn filler, and with Al-3 at.% Zn filler and Ni plating. For all welds,  $\eta$ -Fe<sub>2</sub>Al<sub>5</sub>/Fe<sub>2</sub>Al<sub>5</sub>Zn<sub>x</sub> phase was detected with relatively high intensity on both Al side (Figure 7 (a)) and Fe side (Figure 7 (b)), suggesting that fracture propagated inside the  $\eta$  layer during tensile shear test.



**Figure 7** XRD spectra obtained from fracture surface on the (a) Al and (b) Fe side, respectively.

### 3.3. IMC hardness

It is well known that Zn reduces the hardness of the IMC layer formed at the Al/steel weld interface, so that the hardness of  $\eta$  layer was examined by nanoindentation method. Table 3 summarizes the effect of intermediate metals on the hardness of  $\eta$  layer and the tensile shear strength of the welds. Zn addition reduced the hardness of  $\eta$  layer. The subsequent addition of Ni with Zn further reduced the hardness of  $\eta$  layer. This reduction of hardness might contribute to the effective improvement of the tensile shear strength of the welds, as well as the reduction of the IMC thickness.

**Table 3** Tensile shear strength and hardness of  $\eta$  layer.

Intermediate metals	Tensile shear strength [MPa]	Hardness of $\eta$ layer [GPa]
-	41 ± 4.3	7.1 ± 0.5
3Zn	62 ± 1.9	5.7 ± 0.4
3Zn with Ni plating	120 ± 6.3	4.1 ± 0.3

## 6. Conclusions

In this study, GTAW of AA5052 to IF steel was performed with Al-Zn filler materials and Ni plating, and the effect of simultaneous addition of Zn and Ni on the mechanical properties and microstructure of the Al/steel dissimilar welds were studied. Tensile shear strength of welds was drastically improved by simultaneous addition of Zn and Ni. The improvement of tensile shear strength might be attributed to reduction of the IMC thickness, as well as the reduction of the

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IMC hardness. These results indicated that the simultaneous addition of multiple intermediate metals modified the microstructures and mechanical properties of IMC, resulting in a strength improvement of the Al/steel dissimilar welds.

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