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Article

GTAW of Zinc-Coated Steel and Aluminum Alloy

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Abstract. In this study, effect of zinc-coated layer on steel sheet of dissimilar metals welding between SCGA270C steel and A5052 aluminum alloy by GTAW was investigated. In the experiments, two types of self-brazing welding; 1) welding between non-zinc-coated steel/aluminum alloy, and 2) welding between zinc-coated steel/aluminum alloy, were carried out. The lap joint configuration in which steel was lying on top of aluminum alloy was applied. From the results of zinc-coated steel case, the reaction between the low-melting-point zinc with both molten and solid aluminum alloy provided larger welding width between two metal sheets. Moreover, zinc, which is heavier than aluminum alloy, was fallen down but not well mixed into molten aluminum alloy. Consequently, thick intermetallic compound layer near welding interface between steel/aluminum alloy was formed. Comparison of load resistance between non zinc-coated case and zinc-coated steel case, the wider welding width which consequently improvement the load resistance of the welds was obtained, when using low heat input. However, when applying higher, significant contraction of aluminum welding pool promoted crack along the non-uniform chemical composition zone in case of zinc-coated steel. These cracks were the cause of reduction of load resistance of the welds between zinc-coated steel/aluminum alloy.

Keywords: Dissimilar metals welding, zinc-coated steel, aluminum alloys, GTAW, intermetallic compound phase.

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1. Introduction

Due to significant consumption of energy around the world, which the transportation section is the most critical sector of energy consumption, various concepts and technologies have been introduced to reduce fuel consumption rate of vehicles, such as designing new combustion system, improving engine efficiency, decreasing friction and losses in transmission system, etc. However, one of the most important concept to reduce fuel consumption rate is to decrease the weight of the vehicle by reducing structural weight. This technology is called light-weight structures or hybrid structures.

The dissimilar metals welding, especially welding between steel and various types of light weight alloys, such as aluminum alloys, magnesium alloys, and so on, is one of the fundamental technologies in the production of the light-weight structure. One of the most crucial need of dissimilar metals welding technology in industry is to weld between steel and aluminum alloys. Although, the dissimilar metals welding between steel and aluminum alloys was first published for more than 70 years ago [1], the difficulty to suppress the intermetallic compound phase, which is the severe problems in dissimilar metals welding between steel and aluminum alloys, is still the challenge for welding technologists. Up to now, the most successful welding technique to suppress intermetallic compound phase during welding between bare steel and aluminum alloys is to apply solid state mixing by friction stir welding process, and friction welding, or to apply self-brazing techniques with laser welding, TIG welding, hybrid welding, metal inert gas welding process, etc., as refer in the references [2-15]. However, in some cases, especially for the welding of steel components, which is frequently in direct contact with water and high humidity environment during application, zinc-coated steel is seriously required in order to improve corrosion resistance of steel. Thus, the welding between zinc-coated steel and aluminum alloys is very important. Earlier research of G. Sierra, et. al. [16] used laser beam welding and gas tungsten arc welding (GTAW) to weld galvanized steel to aluminum alloy by applying self-brazing technique. In their work on GTAW, they applied lap joint configuration with aluminum alloy lying on the top and arc was given to steel surface from the bottom. Their results revealed the uniform formation of FeAlSiZn intermetallic compound phase, which lower load resistance than that of aluminum alloy base metal. Junjie Ma, et., al. [17] applied fusion laser welding on joining galvanized high-strength steel to aluminum alloy. They indicated that using two-pass laser welding could provide higher failure value. However, due to using fusion welding, the welding quality was poor compared with self-brazing welding. Also, the cold metal transfer welding was applied to weld galvanized steel and aluminum alloys [18]. This work applied edge lap joint with aluminum alloy lying on top and filled the consumable electrode to its edge. Their results revealed the zinc-rich zone which contained large amount of intermetallic compound phase. There is only one research work which was done by M.Gatzen, et., al. [19], based on our previous survey, to understand the role of wetting of zinc layer on aluminum alloy. Results from their research indicated that oxide layer was the only dominant parameter that affected the wetting of aluminum molten on steel. However, as reviewed above, no research work was yet carried out to understand the effect of zinc-coated layer on welding of steel and aluminum alloy, especially in the case of lying aluminum alloy at the bottom of the lap joint. Thus, in this study, dissimilar metals welding between zinc-coated SCGA270C steel and A5052 aluminum was investigated in order to understand the effects of zinc-coated when aluminum alloy was laid on the bottom of lap joint.

2. Materials and Methods

The 85 mm x 65 mm x 1 mm plates of zinc-coated SCGA270C steel and the A5052 aluminum alloy were used as the base metals in the study. Chemical compositions and mechanical properties of both alloys are shown in Table 1 and 2, respectively.

Table 1. Chemical compositions of base metals.

Materials	Chemical composition (wt.%)						
	Fe	C	Mn	Si	Mg	Cu	Al
Steel	Bal.	0.05	0.17	0.018	-	0.018	0.05
A5052	0.40 (max)	-	0.10 (max)	0.25 (max)	2.2-2.8	0.10 (max)	Bal.

Table 2. Mechanical properties of base metals.

Materials	Yield strength (MPa)	Ultimate tensile strength (MPa)	% Elongation
Steel	233	306	67
A5052	195	230	12

The zinc-coated layer on SCGA270C steel has average thickness of about 10 μm as depicted in Fig. 1. In this experiment, the zinc-coated steel was separated into two groups. For the first one which was called 'non-zinc-coated steel', the zinc-coated layer was removed on the side where was in contact with aluminum alloy during welding process. Removal of the zinc-coated layer was done by using horizontal surface grinders until the total removal depth of about 50 μm, to ensure no remaining of zinc-coated on steel surface. In performing the grinding process, about 5 μm/step of the grinding depth for each grinding step was applied and grinding process was repeatedly performed until total removal depth of about 50 μm was achieved. For the second group which was called 'zinc-coated steel', the zinc-coated layer was left on the steel surface. Before welding, all specimens were cleansed to remove grease and dust by acetone wiping. The lap joint configuration with steel lying on the top of aluminum alloy is shown in Fig. 2.

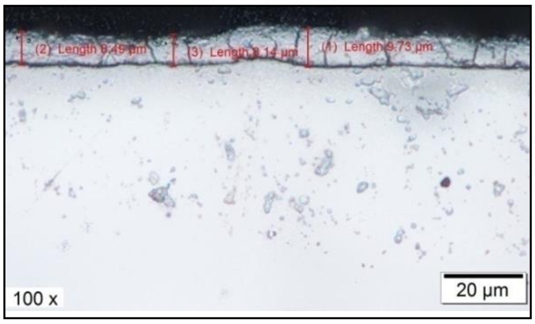


Fig. 1. Cross section of zinc-coated layer on steel which reveals the average thickness of about 10 mm.

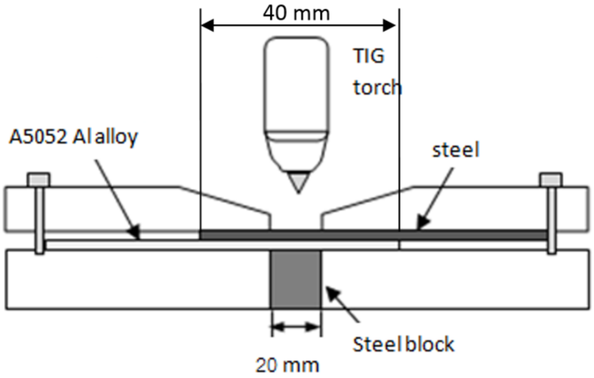


Fig. 2. Lap joint configuration with steel and Al alloy on top and bottom, respectively.

Two groups of welding experiment were carried out. The first group was the welding between non-zinc-coated steel/A5052 and the second group was the welding between zinc-coated steel/A5052. The GTAW welding experiments with direct current electrode negative (DCEN) were carried out by HOBART TIGWAVE 350 AC/DC machine with 2.4-mm-diameter of EWth-2 electrode, welding speed of 0.6 m/min, arc length of 2.4 mm, and distance from specimen surface to touch of 3.2 mm. Argon gas with a flow rate of 8 l/min was provided as the shielding from surrounded environment. Welding currents were varied in the range of 90-140 A in order to obtain the self-brazing welds. Quality of the welds were observed and characterized by cross-sectional observation using Olympus stream optical microscope and JEOL JSM 7800F scanning electron microscope with energy dispersive spectrometer. Furthermore, the tensile-shear test was also carried out by 5582 Instron universal testing machine on the cut weld specimen as shown in Fig. 3. The cutting position on weld specimen for producing tensile-shear testing specimen is shown in Fig. 4.

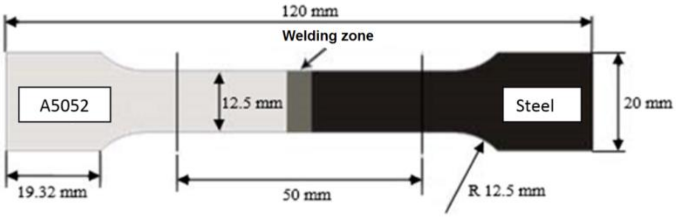


Fig. 3. Shape and dimensions of tensile-shear specimen used in this study.

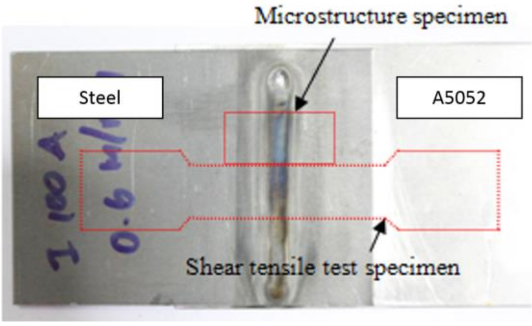


Fig. 4. The cutting position on weld specimen for producing tensile-shear specimen in this study.

3. Results

3.1. Cross-Sectional Observation

-Non-zinc-coated steel/A5052 aluminum alloy welds

Figure 5 shows the cross-sectional observation of the weld between non-zinc-coated steel and A5052 aluminum alloy. From Fig. 5, seven zones in the weld were found. Those zones were categorized into 1) steel fusion zone, 2) steel heat affected zone, 3) steel base metal zone, 4) aluminum fusion zone, 5) aluminum heat affected zone, 6) aluminum base metal zone, and 7) intermetallic compound phase zone. Close observation at the fusion zone of steel and aluminum alloy showed no evidence of direct mixing or contacting of molten steel and molten aluminum alloy during welding. Therefore, very few formation of Fe/Al intermetallic compound phase in the welds was found. The intermetallic compound phase (IMP) was formed only at the welding interface between steel and aluminum alloy, which was called intermetallic compound phase zone. Also, the microstructure in the welding pool indicated that chemical composition of aluminum alloy in its fusion zone was uniform. In the intermetallic compound phase zone, the continuous intermetallic compound layer was formed between steel sheet and aluminum alloy sheet with its largest thickness at the middle of the welding pool and the thickness became thinner near the edge. This intermetallic compound phase layer character is similar to the previous welding research of R. Borrisutthekul, et. al. [8]. Furthermore, after qualitative analyzing of intermetallic compound phase by EDS analysis and matching the chemical composition with phase diagram of Fe/Al, it was indicated that intermetallic compound phase formed in the intermetallic compound phase zone could be Fe_2Al_5, which was similar to the intermetallic compound phase found by other researchers, such as J. Rathod, and M. Kutsuna [20], and so on.

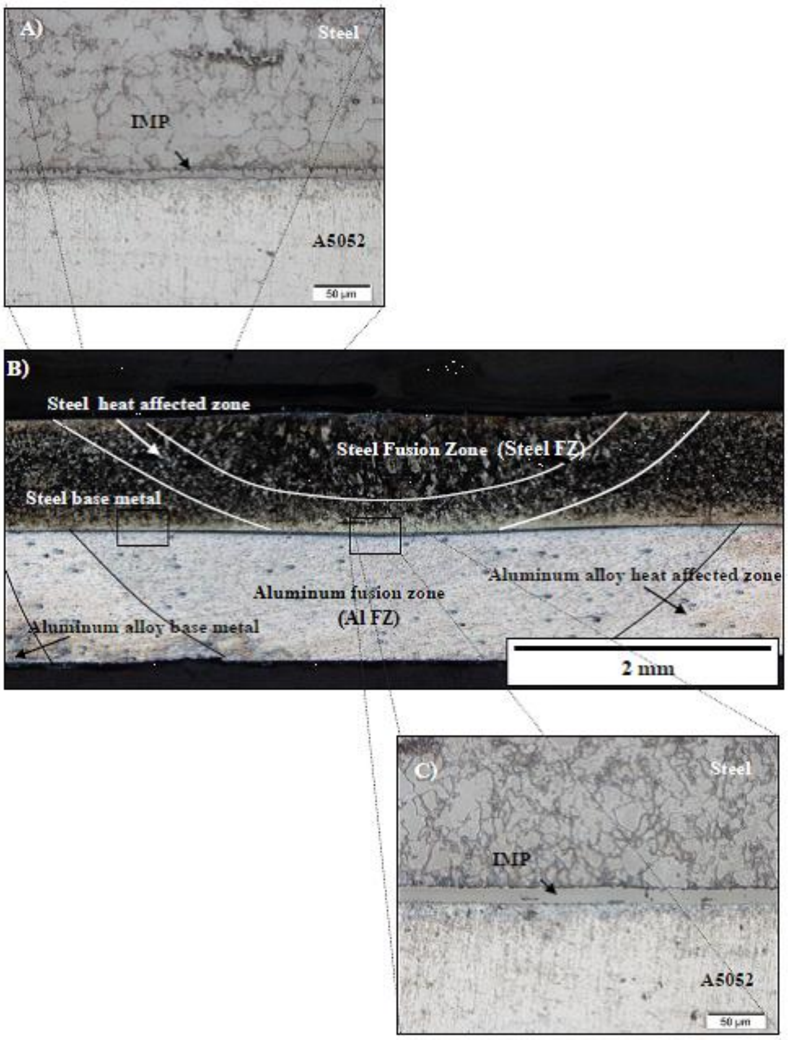


Fig. 5. Example of cross-sectional observation of the weld between *non-zinc-coated steel* and A5052 aluminum alloy (remark : IMP = Intermetallic compound phase).

-Zinc-coated steel/A5052 aluminum alloy welds

Figure 6 shows the cross section observation of weld between zinc-coated steel and A5052 aluminum alloy. From the figure, seven zones in welds were found similar in case of welding of non-zinc-coated steel/A5052 aluminum alloy. However, in welding pool of aluminum alloy, the non-uniform chemical distribution near the welding interface was found. Moreover, the solidification crack was found along the boundary of non-uniform chemical distribution near the edge of weld pool as shown in Fig. 7, when higher welding current was applied for welding.

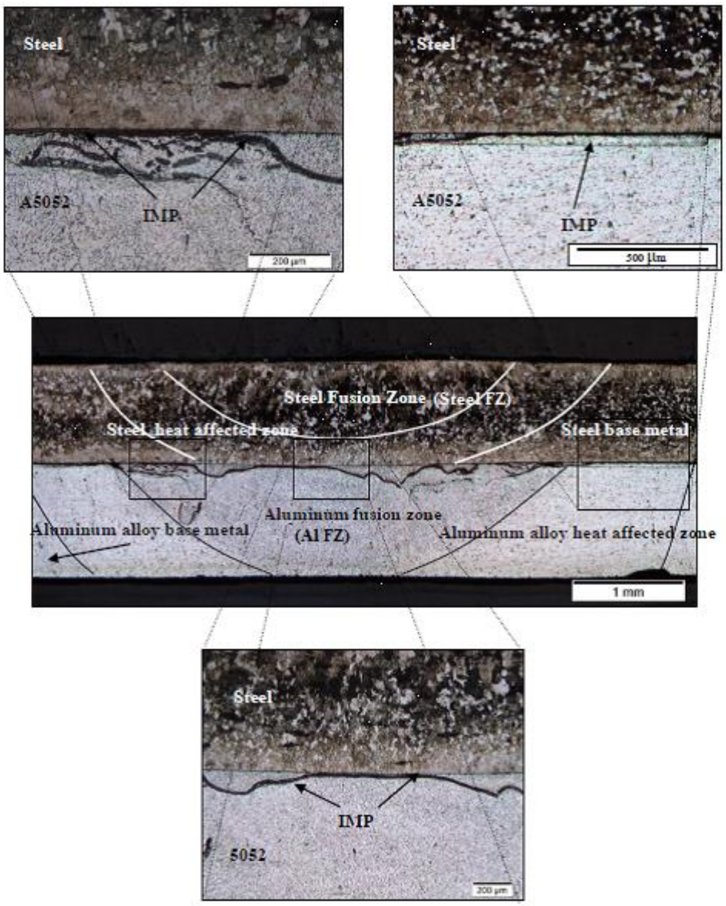


Fig. 6. Example of cross-sectional observation of the weld between *zinc-coated steel* and A5052 aluminum alloy.

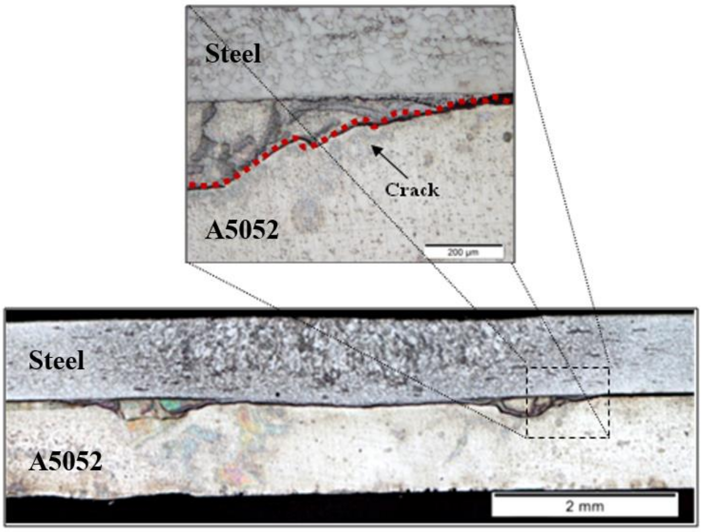
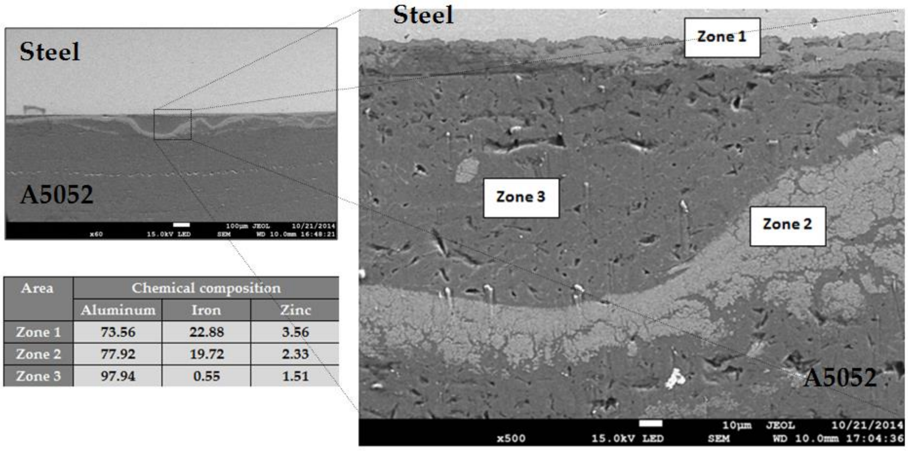


Fig. 7. Example of crack found in welds obtained with applying 140 A of welding current.

The qualitative chemical analysis in the area of non-uniform chemical distribution was done by energy dispersive spectrometer (EDS) as indicated the analysis area and results in Fig. 8. From Fig. 8, it could be realized that there are two zones in non-uniform chemical distribution in aluminum weld pool; 1) white gray line zone(zone 2), and 2) dark gray zone enclosed by white gray line (zone 3). From matching of chemical analysis results of each zones with Fe/Al phase diagram, they indicated that white gray line should be a $FeAl_3$ intermetallic compound phase with few amount of Zn, and dark gray zone should be the eutectic of aluminum and iron with contained few amount of zinc.



Area	Chemical composition		
	Aluminum	Iron	Zinc
Zone 1	73.56	22.88	3.56
Zone 2	77.92	19.72	2.33
Zone 3	97.94	0.55	1.51

Fig. 8. SEM image of non-uniform chemical composition area in weld obtained by applying 120 A of welding current

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Moreover, the intermetallic compound phase in intermetallic compound zone in case of welding zinc-coated steel/A5052 aluminum alloy as depicted in Fig. 6 has two characters. The first intermetallic compound layer character is along the welding interface inside welding pool as shown in high magnification image in Fig. 8. The other character of intermetallic compound phase layer is along the welding interface between solid steel and solid aluminum alloy. The chemical analysis results indicated that first intermetallic compound phase layer character consisted of $FeAl_3$ intermetallic compound phase with contained few among of zinc. For the other character of intermetallic compound phase layer consisted with two layer as shown in Fig. 9. The first layer lying near to steel composed with Fe-Zn intermetallic compound phase and crack inside this layer. The other in which is laid near to aluminum alloy is Al-Zn intermetallic compound phase.

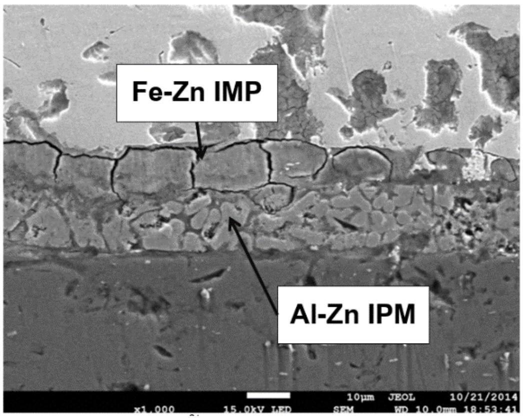

Fig. 9. SEM image of intermetallic compound layer outside aluminum alloy weld pool of weld with 120 A of welding current.

3.2. Welding Width

The welding width between steel/A5052 aluminum alloy in this study was defined as the width of intermetallic compound phase formed along the interface between steel and A5052 aluminum alloy. The welding width and the welding pool width of aluminum alloy were measured according to the cross section of the specimen as depicted in Fig. 10.

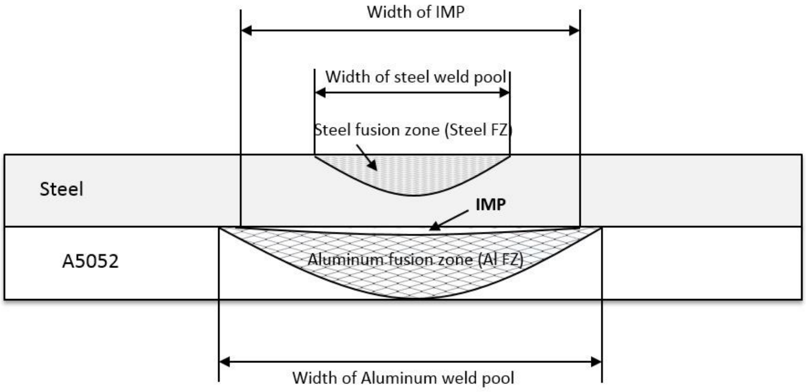

Fig. 10. Schematic representative of the welding width of steel/A5052 aluminum alloy and the welding pool width of aluminum alloy.

The relationship between welding width, aluminum alloy welding pool width and heat input was shown in Fig. 11. The heat input in the study was calculated by using Eq. (1).

$$\text{Heat input } = \frac{IVs}{1000v} \quad \text{(kJ)} \tag{1}$$

where I = welding current (A)
V= welding potential (V)
s= welding distance (m)
v= welding speed (m/s)

From the figure, it was clearly seen that welding width, and aluminum alloy welding pool width of both types of the welds; those were non-zinc –coated steel/A5052 aluminum alloy and zinc-coated steel/A5052 aluminum alloy, increased with increasing of heat applied to welding specimens. When applying the same amount of heat to non-zinc-coated steel/A5052 aluminum alloy and zinc-coated steel/A5052 aluminum alloy, the aluminum alloy welding pools in both cases were formed at similar width level. In case of welding of non-zinc-coated steel/A5052 aluminum alloy, the welding width was narrower than the width of aluminum alloy welding pool. On contrary, the zinc-coated steel/A5052 aluminum alloy welding provided larger welding width when compare to the width of aluminum alloy welding pool. Furthermore, we found that welding between zinc-coated steel/A5052 aluminum alloy gave the welding width larger than that of the welding between non-zinc-coated steel/A5052 aluminum alloy.

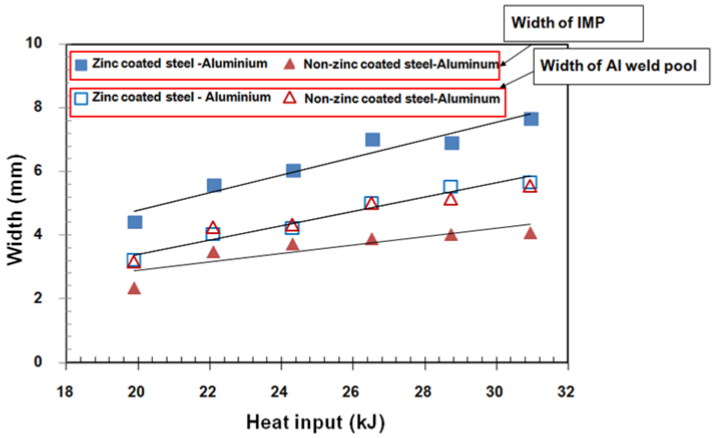

Fig. 11. Relationship between a) intermetallic compound layer width, and b) Al pool width versus heat input for steel/Al weld specimens with and without zinc-coated layer.

3.3 Tensile-Shear Test Results

Figure 12 shows the load resistance of welds between steel and A5052 in both cases. From figure, it was found that increasing heat input to weld in case of welding between non-zinc-coated steel/A5052 aluminum alloy linearly increases the load resistance of weld and it was raised to the maximum load resistance of weld at about 2.4 kN when the highest heat input was applied. On the other hand, increasing heat input to weld between zinc-coated steel/A5052 aluminum alloy could increases the load resistance of weld in case of using low heat input for welding until 24 kJ of heat input used. Then, when applying higher about 24 kJ of heat input, the load resistance of weld decreased with increasing heat input.

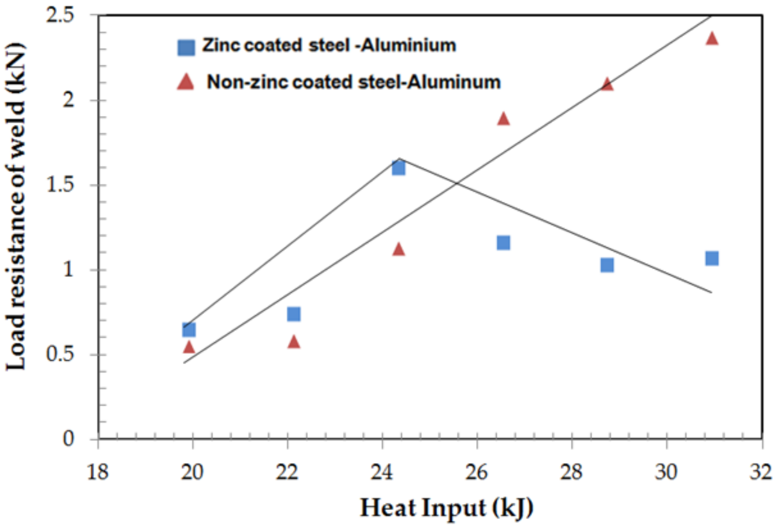

Fig. 12. Relationship between heat input and load resistance of welds.

The examples of fracture paths of weld in both case are shown in Fig. 13. Figure 13 (a) shows the fracture path of welding between non-zinc-coated steel/A5052 was along the intermetallic compound layer. However, in case of welding between zinc-coated steel/A5052, the fracture path of weld was along the non-uniform fusion zone boundary as shown in Fig. 13 (b). As mention before, the non-uniform fusion zone boundary consisted with $FeAl_3$ intermetallic compound phase with contained few amount of zinc.

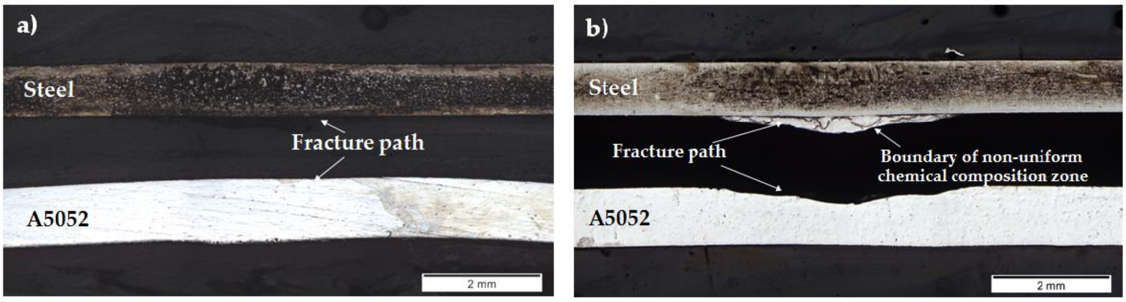

Fig. 13. Example of fracture path of welds obtained with 120 A of welding current after tensile-shear test: a) welding between non-zinc-coated steel/A5052, and b) welding between zinc-coated steel/A5052.

4. Discussion

Firstly, as known, the zinc-coated layer on steel surface was mostly consisted of the low melting point phases. For example, the highest melting point of possible found Fe-Zn IMP on zinc-coated layer has melting at 762 ^{o}C, where is about hundred degrees Celsius above of the melting point of aluminum alloy. Moreover, ternary eutectic of Fe-Al-Zn was lower the melting point than Fe-Zn intermetallic compound phase. Thus, during welding, aluminum alloy molten within welding pool, which normally has the temperature higher than melting point of aluminum alloy, can dissolve Fe-Zn intermetallic compound phase and Zn layer on the surface of steel. However, dissolved Zn from coated layer in aluminum welding pool was not well mixed to aluminum molten metal. The mixing of zinc into aluminum molten was hinder by the stir of molten metals as realized by which non-uniform chemical distribution zone shape like a flow pattern was in welding pool. The poor mixing in welding pool was different results compared with work done by G. Sierra, et. al. [16], which no non-uniform chemical distribution zone was found. The different of our research work and G. Sierra, et., al. work was type of base metal lying on top of lap joint. In our case, steel was laid on the top, which zinc-coated layer was on the top of aluminum molten. When zinc coated-layer was dissolved, the zinc was sunk to aluminum welding pool by gravitation force due to higher density of zinc compared with aluminum molten. While, G. Sierra, et., al. work put aluminum alloy on the top of steel. Thus, the zinc-coated layer was laid under the aluminum alloy welding pool during welding. It resulted that zinc was stayed on the bottom of welding and not found non-uniform chemical composition. Furthermore, using high heat input, which led to larger welding pool, the large contraction of welding pool during solidification provided to high thermal stress in welding pool. While, welding pool has non-uniform chemical distribution zone, intermetallic compound phase in white gray line zone prone to crack and crack was started at near welding pool along boundary of non-uniform chemical distribution zone and aluminum alloy molten.

Secondly, after dissolution of zinc layer into aluminum welding pool, it was allow the aluminum molten to wet on steel surface and to react with iron to form Fe-Al intermetallic compound phase. However, due to having zinc near to interface of welding, the Fe-Al intermetallic compound phase was contained of few amount of zinc. Moreover, because zinc layer on zinc coated layer has melting point lower than A5052 aluminum alloy, the zinc layer was possible to be melted in the welding interface further away from aluminum welding pool and zinc molten reacted to solid aluminum alloy and formed Zn-Al intermetallic compound phase in second intermetallic compound phase zone of welding with zinc-coated steel/A5052. Due to reaction between zinc and aluminum alloy, we could obtain the higher welding width in case of welding between zinc-coated steel/A5052 compared with welding between non-zinc-coated steel/A5052.

Finally, zinc-coated layer provide wider welding width when compared with non zinc coated layer, the load resistance of welds between zinc-coated steel/A5052 was higher than that of welds between non-zinc-coated steel/A5052. However, when using higher heat input, welding between zinc-coated steel/A5052 has crack along boundary non-uniform chemical distribution zone near welding pool edge after welding, the load resistance of welding become lower compared with welding between non-zinc coated steel/A5052, although welding width was higher.

5. Summary

According to above results, we could summarize the effects of zinc-coated layer on dissimilar metals welding between steel/aluminum alloy as follow;

1. The zinc was heavier than aluminum alloy molten. Thus, when lying zinc coated steel on the top of lap joint, it provides the situation that zinc was sunk and poor mixed into aluminum welding pool. Finally, after welding pool solidification, non uniform chemical distribution zone was formed.

2. Due to low melting of zinc-coated layer, it was melted and reacted with solid aluminum alloy at the welding interface between steel and aluminum alloy further away from aluminum alloy welding pool. The reaction between zinc and aluminum alloy to form Al-Zn intermetallic compound phase layer affected the larger welding width in case of welding between zinc-coated steel/A5052 compared with in case of welding between non-zinc-coated steel/A5052.

3. The non-uniform chemical distribution zone in welding pool which was found only in case of welding between zinc coated steel/ A5052 prone to crack, when using high heat for welding. The cracks affected to the lower load resistance of weld between zinc coated steel/A5052 compared with no zinc coated steel/A5052, although the welding width in case of zinc coated steel/A5052 was larger.

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