Numerical Analysis on Thermal Characteristics of Direct Current Pulsed Gas Metal Arc Welded Joints of AA5052 Aluminum Alloy to DP590 High Strength Steel

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In the present study, feasibility of joining 1.2 mm thick AA5052 aluminum alloy to 1.2 mm thick galvannealed (GA) high strength steel DP590 by direct current pulsed gas metal arc welding (DC pulsed GMAW) is studied through experimental and numerical analysis. A comparative study in joining of dissimilar materials by DC pulsed GMAW is performed to realize the effect of different welding parameters on the thermal characteristics of the welded joints and growth of IMC layer thickness. A 3D heat transfer model is developed to estimate the temperature distribution, temperature histories, and the IMC layer thickness of the welded joints. The numerical result showed the fair agreement with experimentally measured average IMC layer thickness within the standard deviation values. An increase of welding current induced longer wet length with lower bead height.

Key Words: Gas Metal Arc Welding, DC pulse, Numerical analysis, Aluminum alloy, Galvannealed steel, Numerical modelling, IMC layer thickness

1. Introduction

Joining dissimilar materials such as steel to aluminum is getting attention in the current transportation industry for improving fuel efficiency. [1] However, joining steel to aluminum is still difficult through fusion welding because of the gap of thermo-mechanical material properties such as melting temperatures. Furthermore, those two materials form Fe-Al intermetallic compound (IMC) which is brittle but requiring essential existence in fusion welding can deteriorate the joint strength. Many of researchers found that the thickness of the IMC layer along the joint interface grows from 723 K with increase of heat input during joining process. [2-6] Especially, it has been reported that galvannealed (GA) steel, which is widely adopted in automobile industry, is difficult to join not only due to the IMC but due to the defects by insufficient melting of zinc coated layer in the steel surface can decrease the wettability of aluminum to the steel. Hence, adopting an appropriate joining method is necessary to join aluminum alloy to GA steel by controlling the defect from zinc coated layer and IMC layer thickness with low level of heat input because the transient thermal cycle and short diffusion time during welding processes can form different thickness of the IMC layer.

Currently, pulsed current gas metal arc (GMA) welding with low heat input is considered increasingly for dissimilar joining of steel to aluminum due to its flexibility and high speed process. In previous studies, joint characteristics of IMC layer in the joint interface and consequent joint strengths are examined in conventional GMA, gas tungsten arc, laser beam, friction stir, and hybrid weldings to join steel to aluminum alloy. [7-12] However, many of studies showed defects in the welded joints and wide variations in IMC layer thickness. Furthermore, Su et al. [7] indicated that alternating current (AC) pulse GMA provides low level of heat input, but the process induces severe porosities due to its change of polarity, split of bubbles by impact, and turbulence of melting pool by arc pressure. Plus, very small numbers of quantitative estimation were tried to investigate the influence of process parameters on the thickness of the IMC layer in the joint interface and bead dimensions.

In this study, therefore, numerical analysis for joining of AA5052 aluminum alloy and DP590 GA galvannealed (GA) steel in lap joint by direct current (DC) pulsed GMA adopting AA4043 filler wires was carried out, and the result was validated with experimental results to optimize the process parameters for sound welded joints. A 3D heat transfer model is developed to compute the temperature field considering temperature dependent material properties and deposited filler wire. The thermal characteristics and dimension of the welded joints is estimated based on the experimentally measured results varying the welding parameters. An analytical model is presented to predict the growth of IMC phase as function of the computed temperature history along the joint interface. The prediction of IMC layer formation after heat conduction analysis is validated with the corresponding experimental results.

2. Experimental procedure

2.1 Experimental investigation
Aluminum alloy (AA5052 H32) and galvannealed steel (DP590 GA) were adopted as base metals. AA 4043 aluminum wire with 1.2 mm diameter was used as filler wire. The chemical composition and mechanical properties of them are shown in Table 1, respectively. Fig. 1 shows the experimental set up in this study. The dimension of the dissimilar base metal plates were 200 mm X 100 mm X 1.2 mm. The aluminum plate was set on the top side of the steel plate. Pure argon was selected as shielding gas at a flow rate of 15 l/min. Referring from previous studies, the welding torch was tilted with 75° angle in opposite to welding direction, and 5° from the steel to the aluminum side. The contact tip to work distance (CTWD) in this study was 15 mm. Table 2 shows the ranges of the welding conditions that are adopted in this study.

### Table 1 Chemical compositions and mechanical properties.

| Mat.   | Mg  | Mn  | Zn  | Fe  | Si  | Cr  | Cu  | Ti  | Al  |
|--------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| AA5052 | 25  | 0.1 | 0.1 | 0.4 | 0.25| 0.15| 0.1 | 0.15| Bal.|
| AA4043 | 0.05| 0.05| 0.1 | 0.8 | 4.5 | -   | 0.2 | 0.1 | Bal.|

| Mat. | C  | Mn  | P   | S   | Si  |
|------|----|-----|-----|-----|-----|
| DP590| 0.09| 1.01| 0.012| 0.005| 0.28|

**Mechanical properties**

| Mat. | Young’s modulus | Yield strength | Tensile strength | Elongation | Poisson ratio |
|------|-----------------|----------------|-----------------|------------|--------------|
| AA5052 | 72 GPa | 183 MPa | 230 MPa | 12 % | 0.33 |
| DP590  | 210 GPa | 420 MPa | 620 MPa | 27 % | 0.3 |

Several studies estimating the bead profiles for butt and lap joint configuration indicate the bead dimension in lap joint is decided by deposition of molten filler wire and aluminum base metal, and the spread of molten filler to the steel surface. The dimension of wire deposited bead profile is presumed as Fig. 2. The profile is surrounded by three lines AE, EO, OB, and two circular arcs BFD and AJD. OC is the height of the bead from the steel surface. It is assumed that the circular arc BFD and AJD are free surface of the filler wire deposit meeting the steel surface at wet angle of \( \alpha_1 \) and \( \beta_1 \). Each center of the circular arc (H1 and H2) are estimated geometrically based on the deposition spread lengths and the wet angles, respectively.

In this study, heat conduction analysis based 3D transient heat transfer model was carried out to estimate the temperature field and the temperature history through the following governing equation.

\[
\frac{\partial}{\partial t} \left( \rho c \frac{\partial T}{\partial t} \right) + \nabla \cdot (k \nabla T) + \frac{\partial}{\partial t} \left( \rho \frac{\partial T}{\partial t} \right) + Q = \rho c \frac{\partial T}{\partial t}
\]  

(1)

Where, \( k \), \( \rho \), \( C \), \( T \) and \( t \) are referred to thermal conductivity, density, specific heat, welding temperature and time variable, respectively. The transverse, thickness and welding directions are represented by X, Y, and Z, respectively. The term \( Q \) depicts internal heat generation, which is applied as multi ellipsoidal volumetric heat input in this study. The volumetric heat input is considered through the term \( \dot{Q} \) as

\[
\dot{Q} = \frac{6\sqrt{\pi} I_{av} I_{av}}{\alpha \beta \gamma} \cdot e^{-3\left(\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2}\right)}
\]

(2)

\( \eta \) is the process efficiency, \( I_{av} \) and \( V_{av} \) are the time averaged welding current and voltage. The term a, b, c is the length to the volume of material affected by the arc heat input in X, Y, Z axis direction, respectively. \( \eta \) is considered as 0.70, and the arc diameter is presumed as three times of the filler wire diameter. The IMC layer thickness can be estimated by the layer growth following the parabolic law of diffusion and its proportional characteristics of the square root of diffusion time. The IMC layer thicknesses corresponding to temperature of interface as \( T_{n+1} \) and \( T_n \) with time of \( t_{n+1} \) and \( t_n \). \( k_0 \), \( q^* \) and R are pre-exponential factor, gas constant, heat of dissolution, and gas constant which are considered as 1.32.
mm^2/s, 226 kJ/mol and 8.31 J/mol K, respectively. [16]

3. Result and discussion

Fig. 3 shows the numerically and experimentally measured cross-sectional view of bead profiles for three different welding conditions as welding current 74, 63, and 51 A, respectively. Fig. 3 (a) to (c) are numerically achieved bead profiles, and (d) to (f) are corresponding experimental results. In Fig. 3 (a) to (c), the bead is formed as encompassed area which is coloured with green (880 K, solidus temperature of the aluminum) to red (1783 K, liquidus temperature of the steel) and un-melted steel surface. The temperature distribution of the welded joints below the liquidus temperature of the steel (1783 K) but higher than the liquidus temperature of the aluminum (925 K) allows the molten aluminum and wire to be spread to the steel side to be brazed. Unlike zinc coated layer in galvanized (GI) steel, the melting temperature of zinc layer which is alloyed with Fe in the GA steel can be confirmed as 1203 K through the Fe-Zn phase diagram. [17]

Compared to welding current 51 A condition, it can be inferred that the zinc layer of the GA steel in 74 and 63 A condition might be sufficiently molten, and joined the aluminium to the steel. However, it can be also inferred that there is possibility of some defects such as pin hole or blow hole, because the temperature of the bead under the higher welding speed was raised upper than the evaporation temperature of zinc (1180 K), so some of zinc vapor which is evaporized from the surface could not escape from the molten aluminum and filler wire during welding.

In Fig. 3 (d) to (f), it is confirmed that the welded joints is free from porosities in welding current of 51 A condition (Fig. 3 (f)), because lower welding speed provides the enough time to evaporized zinc to escape from the molten materials. In Fig. 3 (d) and (e), 63 A condition showed blow holes in the welded joints, and 74 A condition showed small amount of pin hole whose amount can be ignorable was observed due to its faster solidification of the molten material with higher welding speed deterred the growth of porosity. The dimensions of bead profiles corresponding to Fig. 3 (d), (e), (f) are shown in Table 3. It is found that the welding current of 51 A condition formed the highest reinforcement and the shortest wet length, because the lowest heat input by the lowest welding current caused the lack of spread of the molten filler metal. On the other hand, an increase of welding current resulted in lower bead reinforcement and longer wet length. Thus, it can be inferred that the formation of bead is decided by the surface tension of the molten materials, but the higher arc pressure in higher heat input increase the wettability of aluminium to steel in the temperature below than the liquidus temperature of the steel.

Table 3 Bead dimensions.

| Current | 51 A | 63 A | 74 A |
|---------|------|------|------|
| Reinforcement | 3.02 mm | 2.96 mm | 2.68 mm |
| Wet length | 3.87 mm | 4.82 mm | 4.49 mm |
| Wet angle | 100.39° | 86.61° | 75.75° |

Temperature distribution of dissimilar materials welded joints with different welding current is compared to investigate the thermal characteristics of the dissimilar materials welded joints. Fig. 4 (a) to (f) describe the numerically analyzed temperature distribution of top surface and cross-section in welding current of 74, 63, and 51 A conditions, respectively. In Fig. 4 (a) and (d), the maximum temperature is appeared as 1553.2 K, and the wider temperature distribution is observed in the aluminum alloy side. In Fig. 4 (b) and (e), and Fig. 4 (c) and (f), the maximum temperature are appeared as 1467.9 K and 1368.3 K. These two conditions show asymmetric temperature distribution as similar with Fig. 4 (a) and (d). The wider temperature distribution in the aluminum side than in the steel side is because higher thermal conductivity of the aluminum alloy allows the heat to be conducted faster in the aluminum alloy.

The estimated temperature history at the joint interface in 74 and 51 A welding current conditions were adopted to estimate the Fe-Al IMC layer thickness. The locations of measured temperature
history in the joint interface is described in Fig. 5 (a). Fig. 5 (b) shows the comparison of the temperature histories. The maximum temperature in each location was 1427.4, and 1266.9 K at 74 A condition, and 1255.9, and 1145.3 K at 51 A condition, respectively. Fig. 5 (c) and (d) show the the maximum temperature at the joint interface and the estimated IMC layer thickness. The IMC layer thickness was estimated by adopting the result of numerically computed temperature histories of TH1 and TH2, and the result was substituted into the equation (3) to aggregate. In 74 A condition, as the maximum temperature at the interface is decreased while the measured location is moved from the arc center to the arc edge, the estimated IMC layer thickness is also decreased from 3.86 µm to 2.16 µm. It can be inferred that the surge of heat generation per unit time in the welded joints at higher energy concentration from the arc increased the IMC layer thickness. Similarly, 51 A condition show the decrease of IMC layer thickness from 0.36 to 0.15 µm, which can be neglectable, as the decrease of heat generation per unit time in the welded joints. Moreover, 51 A condition is also expected that the IMC layer is difficult to be formed due to the insufficient maximum temperature and the time duration of temperature upper than melting point of the zinc layer in GA steel surface (1203 K).

Following the locations in Fig. 5 (a), the average values of the IMC layer thickness by the 74 and 51 A welding current condition were measured, and the result of numerical estimation of IMC layer thickness was validated. The SEM macrographs of Fe-Al IMC layer at 74 A is shown in Fig. 6 (a) and (b), and that at 51 A is shown in Fig. 6 (c). In welding current 74 A condition, the IMC layer thickness was increased from TH2 to TH1 because the higher amount of heat generation from higher energy density in the arc generated more drastic temperature variation in the unit time. Moreover, the serrated type morphology of IMC layers towards the aluminum side is observed due to the non-uniform diffusion between Fe and Al at the joint interface. In 51 A condition (Fig. 6 (c)), it is observed that the zinc layer is still remained instead of the formation of the IMC layer due to the lack of heat input could not melt the zinc layer sufficiently as shown in EPMA (Fig 6 (d)).

Fig. 7 (a) plots the comparison of numerically estimated and experimentally measured IMC layer thickness with standard deviation. This indicates an increase of heat input to the volume of the materials at the unit time increase the estimated IMC layer thickness from 0.36 to 3.86 µm, and corresponding experimental results shows agreeable thickness from 0 (approximate value), 1.90 (±0.67), and 3.96 (±0.81) µm. It is confirmed that the numerically analyzed IMC layer thickness at the joint interface shows reasonably fair agreements to the corresponding experimental results, and 74 A conditions satisfied the requirement of IMC layer thickness (less than 10 µm) to get sound welded joints. [18,19] As a result of experimental and numerical analysis, it is expected that sound welded joints can be achieved by welding current 74 A condition than the others through the proper thickness of IMC layer, free from defects, and sufficient melting of Fe-Zn layer on the steel surface.

To investigate the reliability of influence of IMC layer thickness on the weldability of dissimilar materials welded joints by DC pulse GMA, tensile-shear strength test was proceeded. Fig. 7 (b) shows the average failure load of welded joints at 51, 63, and 74 A welding current. The maximum failure load was achieved as 1.97
kN in welding current 74 A condition due to the zinc layer on the steel surface has been molten sufficiently and formed the proper thickness of IMC layer during joining process as similar as the numerical analysis. In 63 A and 51 A condition, the average failure load was decreased drastically as 1.34 and 0.86 kN, respectively. The formation of IMC layer thickness had fair agreement with the estimated thickness, but insufficient melting of Fe-Zn layer and formation of blow hole by evaporized zinc induced imperfect joints.

Consequently, it is realized that the growth of IMC layer is affected by heat generation in the volume of the materials at the unit time after the sufficient melting of Fe-Zn layer in aluminum-GA steel joining process.

![Image](image_url)

**Fig. 7** Validation of estimated IMC layer thickness and weld strength

### 4. Conclusions

1.2 mm thickness aluminum alloy AA5052H32 and galvannealed high strength steel DP590 GA, were joined by DC pulsed GMA welding, and its IMC layer formation is predicted. A methodology is proposed to estimate the IMC layer thickness as a function of temperature variation within the unit time.

1) The the wettability of the bead formed on the un-melted steel surface within the aluminum solidus temperature is affected by the higher temperature than melting point of zinc coated (Fe-Zn alloy) layer.

2) An asymmetric temperature distribution which is stiffer temperature gradient in steel side is observed due to the higher thermal conductivity of the aluminum.

3) The estimated IMC layer thickness and experimentally measured showed fair agreement. It is confirmed that increase of IMC layer is due to the higher heat generation per unit time from the center of heat source after the sufficient melting of Fe-Zn layer.

4) It is realized that the mechanism of zinc from Fe-Zn alloy layer during the welding process decides the joints quality.

The methodology proposed here is expected to provide a step towards the development of quantitative routes for the selection of proper parameters in joining aluminum alloy to GA steels.

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