Joining of AZ31 Magnesium Alloy and Steel Sheet under Four Different Coating Conditions Based on Gas Metal Arc Weld-Brazing

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Dissimilar joining of AZ31 Mg alloy to various steel sheets with different coatings (galvanized (GI), galva-annealed (GA), cold rolled bare (CR), and aluminized (Aluminized) steel sheets) was performed by gas metal arc brazing. An excellent weld bead appearance was obtained in all cases and the wettability of the AZ31-GI steel joint was better than that of the other brazed joints. Moreover, the AZ31-CR steel brazed joint exhibited the highest tensile-shear strength. The fracture behaviors of the four brazed joints were different and depended mainly on the chemical composition (especially the Zn content) of the coating layer. Owing to the weak bonding between the Mg-Zn eutectic phase and the Fe-Al intermetallic compound, which formed at the interface of the joint, the strength of the Zn-coated steel (GI and GA steel sheet) joints was lower than that of their non-Zn-coated counterparts.

Keywords: gas metal arc brazing, magnesium alloy, steel, dissimilar metal joining, transition layer, microstructure

1. Introduction

Magnesium alloys are the lightest structural metals, and can be used in various applications, owing to their low density, high specific strength, excellent heat dissipation, damping, and electro-magnetic shield capacity. However, steel is the most frequently used structural metal and industrial demand for weight reduction in automotive applications, by joining dissimilar materials of steel and magnesium alloys, has increased; high-strength low-weight materials produced at low cost, are highly desirable. Joining steel and magnesium alloys via conventional fusion welding is difficult, owing to the large differences in their melting points and almost-zero solubility between iron and magnesium. In other words, magnesium alloys and steel do not react chemically with each other and barely form solid solutions or compounds; obtaining a stable interlayer is therefore difficult.

As such, magnesium alloys and steel were joined primarily via solid-state welding such as friction stir welding (FSW), diffusion bonding, etc.

The welding of magnesium alloy and steel, via FSW, has been extensively investigated. Watanabe et al.1) performed the first study of the FSW weldability of AZ31 magnesium alloy and SS400 steel; they determined the effect of pin rotation speed and the pin plunging position on the strength and microstructure of the butt-welded joint. The maximum strength of the joint was ~70% of the strength of the magnesium base metal. In addition, Chen and Nakata2) examined the microstructure and determined the mechanical properties of the lap joint formed between AZ31 magnesium alloy and a Zn-coated steel. The evolution of the interface microstructure and the joining mechanism were elucidated. They reported that the zinc coating promoted the formation of a Mg-Zn eutectic structure, spread along the interface, and improved the weldability of magnesium alloy to steel. Moreover, Liyanage et al.3) examined the microstructural features and evaluated the overlap shear-strength properties of friction stir spot welds (FSSW) between AM60 magnesium alloy and DP 600 dual phase steel. Jana et al.4) evaluated the feasibility of joining AZ31 magnesium alloy and two different galvanized steel sheets, namely, electrogalvanized mild (EG) steel and hot-dipped galvanized (HDG) high-strength low alloy (HSLA) steel. The fatigue behavior of FSW-produced Mg/steel lap joints has also been investigated5). Furthermore, Schneider et al.6) determined the characteristics of the interface between an AZ31B magnesium alloy and a mild steel with/without zinc coating. They reported that the zinc coating functions as a flux and thereby results in the formation of a liquid eutectic layer during the process. In addition, Wang7) and Zhang8) determined the feasibility of FSSW for Mg/GI steel overlap joints. These studies revealed that the inherently complex FSW and FSSW processing heads impose size and shape limitations on the resulting product.

Fusion welding processes have been used in order to overcome the disadvantage of solid-state welding between magnesium alloys and steel; these processes include a laser hybrid9–21), laser braze22–28), and resistance spot welding29–31) on the dissimilar joint. Liu9–15) and Qi16–19) have applied a laser-arc hybrid process to various dissimilar joints of magnesium alloy and steel. The laser-gas tungsten arc (GTA) hybrid process was first applied to the lap joint of an AZ31B magnesium alloy and 304 stainless steel9). During the process, weld penetration was induced by the laser and pool stirring was performed via GTA welding. The joints fractured at the interface between the magnesium alloy and the steel. In addition, metallic oxides formed at the interface resulted in poor mechanical properties of the weld joints. These issues can be resolved by the addition of other alloying elements that can interact with both alloys, thereby yielding a strong interlayer. Liu and Qi characterized the joints formed between AZ31B magnesium alloy and Q235 mild steel, when Cu, Ni, and Sn10–20) interlayers are added via the hybrid laser-GTA welding technique. Owing to the formation of solid solutions and intermetallic compounds, the resulting joint strength was almost the same as that of AZ31B.

Laser braze welding also was applied to the joint of magnesium alloy and steel22–28), Wahba and Katayama22) characterized the lap joint formed between an AZ31B magnesium
alloy and a zinc-coated steel. Li et al. and Tan et al.\textsuperscript{23–28} examined the microstructure and evaluated the mechanical properties of laser welded-brazed joints formed between magnesium and Zn-coated/non-Zn-coated steel. These studies revealed that, in the case of the galvanized steel, the crack propagated along the interface between the Mg-Zn reaction layer and the pre-existing Fe-Al layer, owing to weak bonding between these layers. However, in the case of the non-coated steel, the newly formed Fe-Al phase strengthened the bonding of the interface.

In the case of resistance spot welding, it was examined joints formed on AZ31B/zinc-coated DP600 steel by Liu et al.\textsuperscript{29} and AZ31B/hot-dip galvanized HSLA steel by Xu et al.\textsuperscript{30}, and determined the mechanisms governing dissimilar joining\textsuperscript{29}. The joining mechanism was explained on the basis of braze welding, solid-state bonding, and soldering. In another study, the mechanical properties and fracture behavior of Mg-to-steel dissimilar resistance spot welds were determined and compared with those of Mg/Mg welds\textsuperscript{31}).

Recently, Cao\textsuperscript{32} determined the feasibility of cold metal transfer (CMT) welding of AZ31 to galvanized mild steel lap joints. CMT welding is a modified gas metal arc (GMA) welding process that uses a new method of droplet detachment based on short circuit welding, and the reduced thermal input of CMT welding leads to advantages such as low distortion and high precision. In that study, it was reported that the strength of the CMT weld-brazed AZ31-galvanized mild steel joint is similar to that of the AZ31-AZ31 welded joint.

Therefore, in the present study, to study the dissimilar joining of AZ31 magnesium alloy and steel sheet according to the coating conditions, it was investigated that gas metal arc (GMA) brazing between an AZ31 magnesium alloy and steels with different coatings (galvanized (GI), galva-annealed (GA), cold rolled bare (CR), and aluminized (Aluminized) steel sheets) which are mainly used as surface coating conditions of steel for automobile components. GMA brazing was selected because it is represent welding method for the automobile component with resistance spot welding. CMT welding is used as a low-heat-input arc welding process. The microstructures of the interfacial and fracture surfaces of the joint are compared, and the relationships between the microstructure and the mechanical properties are determined.

2. Experimental Setup

A 2.0-mm-thick AZ31 magnesium alloy and four types of steel sheet, with different coatings, were used as the base materials in this study; GI, GA, CR, and Aluminized steel sheet were investigated. The thickness of the steel sheet and diameter of the AZ31 magnesium filler wire were 1.0 mm and 1.2 mm, respectively. In the time between experiments, the filler wire was kept in a vacuum pack, in order to prevent oxidation. The chemical compositions of the base materials and filler wire are shown in Table 1 and Table 2.

GMA brazing was performed in a special short-circuit mode; CMT was applied, and the filler wire was placed at an angle of 60° from the specimen surface and 100° toward the forward direction. Figure 1 shows a schematic of the lap joint configuration used in this study. The specimen was subjected to lap-fillet joint welding and the AZ31 magnesium alloy was attached to the steel sheet with an overlapping length of 30 mm. In addition, argon shielding gas was supplied, at a flow rate of 15 L/min, to the specimen surface to prevent oxidation during welding. Welding parameters were fixed in order to maintain the same heat input to the specimen during GMA brazing. The welding voltage, current, and speed were 10.6 V, 90 A, and 0.4 m/min, respectively.

The composition of each coating layer is shown in Fig. 2. The GI steel sheet is composed of base steel and an almost pure 10-μm-thick Zn coating layer, whereas the GA steel sheet consists of an 8-μm-thick Zn-Fe alloy layer. Moreover, the aluminized steel sheet is composed of base steel, a 25–30-μm-thick AlSi coating layer, and an intermetallic compound layer. In contrast to the other steels, the CR steel sheet did not have a coating layer.

Tensile tests were conducted with machined specimens

![Image](314x286 to 539x408)

![Image](320x418 to 533x547)

**Fig. 1** Schematic of the arc-torch configuration, (a) Arc-torch configuration, (b) Prepared specimen for tensile test.
based on ISO 4136 standard as shown in Fig. 1(b), which has 25 mm width of parallel length, 50 mm gauge length and 90 mm length between hydraulic gripping parts. The tensile-shear strength of the lap joint was measured at a crosshead speed of 5 mm/min, by using a universal testing machine. Furthermore, the morphology of etched and non-etched samples was examined; the etchant was composed of 10 mL, 4.2 g, 10 mL, and 70 mL of acetic acid, picric acid, H2O, and ethanol, respectively. The microstructures of the weldment were examined by using a scanning electron microscope (SEM), equipped with an energy-dispersive X-ray spectrometer (EDS). In addition, the distribution of elements was determined via electron probe microanalysis (EPMA).

3. Results and Discussion

3.1 Weld bead appearance and wettability of the weld-brazed joints

Wetting angle and joint distance significantly affects strength of the joint. Generally, longer joint distance and sharp edge angle more effective to enhance the strength due to release the stress concentration. In arc welding process, bead appearance was severely managed based on as AWS D1.1 standard. The weld bead appearance and cross-section of each weld joint are shown in Fig. 3. In this study, we obtained a sound bead appearance, without delamination, and defect-free joints regardless of the coating type and condition of the steel surface.

The wetting angle and wetting distance were measured, in order to determine the wettability of the four weld joints. As Fig. 4 shows, the wetting distance (11 mm) of the AZ31-GI steel joint is the longest, whereas the wetting distance (~8 mm) of its AZ31-CR and GA counterparts is the shortest. However, the wetting angle exhibits the opposite tendency, i.e., the wetting angle of the AZ31-CR and GA steel (120°) is the highest and the angle (i.e., 50°) of the AZ31-GI is the lowest. We used the same filler wire for all of the welding samples; nevertheless, the wettability of the AZ31-GI steel joint is better than that of the other samples. It seems that the wettability of the dissimilar joint is affected by the composition of coating layer. It was reported that Al-Si coating layer on the steel sheet promotes wetting of the Mg-Al filler alloy [23]. Also, the addition of Zn had an influence on the wetting or spreading behavior of liquid filler metal. Li et al. [23] reported that the spreading ability of liquid filler on steel with Zn coating was superior to that without Zn coating under the same welding conditions on the joining of Mg alloy AZ31 to Zn-coated steel. In this study, wettability of AZ31-GI steel
joint and AZ31-Aluminized steel joint are better than that of AZ31-CR steel joint, as mentioned literature. However, in case of AZ31-GA steel joint, wettability is similar with the AZ31-CR steel joint.

3.2 Strength of the weld-brazed joints

The coating layer of the steel may influence the mechanical properties of the lap joint; this influence was determined by measuring the tensile-shear strength of the brazed joints. To compare the strength of the overall specimens, failure load was divided with a width of parallel length. As Fig. 5 shows, the AZ31-CR steel brazed joint has the highest strength of all four joints. Fracturing of the AZ31-CR and AZ31-Aluminized steel brazed joints occurred in the weld metal. However, in the case of the GI and GA steels, fractures occurred on the interface of the joint even AZ31-GI joint had an excellent joint wettability. The fracture mechanism will be discussed in detail in section 3.4.

3.3 Microstructure of the brazed joints and thickness of the transition layer of the brazed joints

Figures 6 (a)–(e) show the microstructure of the brazed joints and the thickness of the transition layer of the GI, GA, CR and Aluminized steel sheets and AZ31 alloy lap joints. The microstructures of the interfacial surface of the weld joints were examined via SEM. Transition layers are generated by the reaction between the filler metal and the coating layer of the steel sheet, and can be distinguished on the basis of their morphology. In the case of the AZ31-GI steel joint, a eutectic-structured transition layer formed along the interface. The 22-µm-thick transition layer of the AZ31-GI and 2-µm-thick layer of the AZ31-CR steel lap joint are the thickest and thinnest transition layers, respectively.

3.4 Bond mechanism of weld-brazed joints

The thickness and composition at the transition layer of the interface were determined, in order to elucidate the bond mechanism of the brazed joints; the composition of the coating layer and formation of phases at the interface were considered. Figure 7 shows the chemical content distribution and schematic of the transition layer at the interface of the GI, GA, CR and Aluminized steels and AZ31 Mg alloy lap joints. In the case of the AZ31-GI steel joint, the interface of the brazed joint is composed of an α-Mg and Mg-Zn eutectic layer, which has a high Zn content; the 25-µm-thick transition layer of this joint is composed of an Fe-Al intermetallic compound which is estimated the FeAl or Fe3Al phase, which has a high Al content, as determined via EDS analysis. Tan25,26) identified the FeAl and Fe3Al phases of Fe-Al intermetallic compound and Mg-Zn eutectic structure between Mg-Zn coated steel dissimilar joint by transmission electron microscopy (TEM) and selected area electron diffraction pattern (SADP). Conversely, a weakly developed eutectic layer and a small island, which consists of the eutectic microstructure and transition layer, occur at the interface of the AZ31-GA steel joint. The transition layer is composed of binary Mg-Fe, as determined via EDS analysis. Moreover, the layer has a thickness of 7–8 µm, which is less than half the thickness of the transition layer of the GI joint.

In GA and GI steels, the bare base metal is covered with a thin Zn-based coating layer which, in the case of the GA steel, consists of 10 mass% Fe. However, the coating layer of the GI steel is composed mainly of Zn, and is thinner than that of the GA steel. The coating layer of GI steel sheet consists of four separate layers. The first three layers, on the steel side, are composed of a mixture of Fe and Zn, whereas the surface layer is typically composed of 100% Zn. In contrast, the coating layer of a GA steel sheet is composed of an alloy of Zn and Fe, and the surface layer is composed of a zeta phase. Therefore, in case of the AZ31-GI steel joint, the pure Zn on the surface of the GI coating layer can easily react with Mg, leading to the formation of a Mg-Zn eutectic phase, via diffusion of Zn to the braze joint; the reaction occurs more readily in this joint than in its GA counterpart, whose surface layer is composed of an alloyed zeta phase. During the brazing of AZ31 on GI steel sheet, liquid Zn, which has a low melting point, contacts the Mg-based molten metal and rapidly penetrates the molten pool. This leads to the formation of a Mg-Zn eutectic microstructure at the interface of the joint. On the
other hand, the amount of diffusible Zn in the GA steel sheet is inadequate for the formation of the Mg-Zn eutectic layer. Therefore, during solidification, Fe located near the solid-liquid interface combines with Al, Zn, thereby resulting in the formation of a transition layer, whose composition differs from that of the eutectic layer.

The 5-μm-thick transition layer at the interface of the AZ31-Aluminized steel joint, is composed of ternary Fe-Mg-Al. This layer has a maximum Al content of 15 mass%, which, as shown in Fig. 7(c), is significantly higher than the content outside the layer. This indicates that the reaction occurred between Fe and Al only, because Fe and Mg cannot react with each other. As a result, the Fe-Al binary phase (rather than the ternary phase) occurs at the interface.

The transition layer of CR steel sheet, such as GI and Aluminized steel sheet, has a maximum Al content of 10 mass%. An Al-containing transition layer was formed at the interface of each brazed joint, indicating that Al may play an important role in the formation of the transition layer. Fe and Al react in all cases, leading to the formation of a Fe-Al compound or solid solution at the interface of the brazed joint.

The compositions at the interface were determined via SEM-EDS (as shown in Fig. 8) in order to distinguish between the fracture sites and the phases at the interface. Fracture sites in the AZ31-GI steel joint are located between the Mg-Zn eutectic layer and Fe-Al binary phase. Fe was absent from the weld metal side of the fracture interface, which contained large amounts of Zn. However, cellular-shaped phases occurred at the interface, as shown in weld metal side of Fig. 8(a). The cellular-shaped phases are the representative proof of solidification cracking formed by the fracture of liquid. In other words, these phases form at the interface during solidification, and act as crack-initiation sites. In fact, the decrease in the strength of the bonding or joining may be attributed to these cracks. As Fig. 8(b) shows, fracture of AZ31-GA steel joint was located between transition layer and weld metal. A small island of Mg-Zn eutectic structure could be investigated (white dotted circle). EDS results show that Fe is absent from the filler metal side, indicating that the bonding strength of the transition layer and steel sheet is higher than that between transition layer and weld metal. From the results, chemical reaction affected from consistence of coating layer which made a difference in eutectic structure and transition layer. GI joint included large area of weak interface which was consisted of eutectic structure and Fe-Al phase compound, but in GA joint contained much small amount of eutectic structure than GI joint. Hence the strength of GI joint is lower than that of GA joint. In the case of non-Zn-coated CR and Aluminized steel joints, fracture occurs at the weld metal or transition layer, as previously shown in Fig. 5. Frac-
ture occurs in the weld material of the AZ31-CR steel joint. Compared with the tensile-shear strength of the Aluminized and CR steel joints, the strength of the AZ31-Aluminized steel joint is lower than that of the AZ31-CR steel joint. Figure 8(d) shows both sides of the fracture interface at the root of the bead, where fracture is initiated in the AZ31-Aluminized steel joint. The fracture surface has a smooth interface, and the fractures were probably initiated at the transition layer, owing to the Fe content of the transition layer side. This fracture propagates along a direction perpendicular to the interface, until the joint fractures. Tan\textsuperscript{25,26} considered the fracture mechanism of the Mg/steel brazed joint: the decrease in tensile strength and consequent interfacial failure of the Mg alloy/steel brazed joint with Zn coating, was attributed mainly to the weak bonding between the Mg-Zn phase and the Fe-Al layer. Similarly, the strength of the Mg alloy/steel brazed joint, without Zn coating, varied with the thickness of the Fe-Al phase. In this study, the strength of the brazed joint

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**Fig. 7** Chemical content distribution and schematic of the brazed joints.
with Zn coating (GI and GA steel) is attributed to the weak bonding between the Mg-Zn eutectic phase and the Fe-Al phase, as reported in previous studies. The difference of continent of initial coating layer between two of them make structural alteration. GA steel sheet consisted with Zn-Fe alloy layer and these composite layer got a different melting temperature and energy level to form eutectic structure. The higher strength of the brazed joint without Zn coating (CR and Aluminized steel), compared to that of its Zn-coated counterparts, results from the formation of the Fe-Al phase at the transition layer. However, the relationship between the strength of the brazed joint and the thickness of the Fe-Al phase could not be investigated in the present study; this relationship will be investigated in future work.

4. Conclusions

An AZ31 Mg alloy was weld-brazed to steel sheet with four types of coating (GI, GA, CR, and Aluminized steel), and the properties of the weld-brazed joint were evaluated. The conclusions of this study are summarized as follows:

1. A good weld bead appearance and defect-free joints were realized in all four cases. The wettability of AZ31-GI steel joint and AZ31-Aluminized steel joint were better

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**Fig. 8** Microstructure and composition at the failure interface of the (a) GI, (b) GA, (c) CR, and (d) Aluminized steels and Mg alloy lap joints.
than that of AZ31-CR steel joint. However, the wettability of AZ31-GA steel joint is similar with the AZ31-CR steel joint. This indicates that the wettability is generally influenced by the composition of coating layer.

(2) The bonding strength of the AZ31-GI and GA steel joints was lower than that of the CR and Aluminized steel joint. The Mg-Zn-Al ternary phase forms on the transition layer, and a thick transition layer is obtained, in the case of the GI and GA steel joints. However, in the case of CR and Aluminized steel joints, the Al content plays an important role in the formation of the transition layer, and a thin layer is obtained.

(3) The failure site was identified by examining the interface between the brazed joint and the weld metal. Based on the analysis of the fracture surface, the strength of the Zn-coated brazed joint (GI and GA steel) was attributed to the weak bonding between the Mg-Zn eutectic and Fe-Al phases.

(4) Zn, as an alloying element on the coating layer, had a positive influence on the wettability. However, owing to the formation of a weak joint interface between the Mg-Zn eutectic and Fe-Al phases, the Zn coating layer had a negative effect on the bonding strength.

REFERENCES