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# Friction Stir Lap Joining of AC4C Cast Aluminum Alloy and Zinc-coated Steel

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**Abstract.** AC4C cast aluminum alloy and zinc-coated steel were friction stir lap welded, and the microstructures and mechanical properties of the joints were examined and analyzed. Experimental results show that the welding speeds have a significant effect on the tensile properties and fracture locations of the joints at a rotational speed of 1500 rpm. When the welding speed is higher than 60 mm/min, the joints fracture in the zinc-coated steel base material and the tensile strength is equal to that of the zinc-coated steel; when the welding speed is lower than 60 mm/min, the joints fracture in the interface and the shear strength is about 50 MPa. The change of the fracture locations is attributed to the presence of large quantity intermetallic compounds adjacent to the interface of the joints. The composition and formation mechanism of the intermetallic compounds and its effect on the mechanical properties of the joints were discussed.

## Introduction

The need of light weight in automotive body construction leads to the increasing use of the combination of steel and Al alloy in fabrication of vehicles [1]. At present, the following main welding technologies have been employed to join Al alloy and steel: ultrasonic welding, explosive bonding, electric discharge bonding and friction welding. On the other hand, as an emerging welding technology, friction stir welding (FSW) is one of the most popular bonding methods for joining dissimilar materials. Most studies mainly focus on the dissimilar metal joining of Al alloy and steel; while, little research have involved joining of Al alloy and zinc-coated steel [2-4]. Studies on this topic are important for revealing and comprehending the friction stir weldabilities of Al alloy and zinc-coated steel. In this study, AC4C cast aluminum alloy and low carbon zinc-coated steel are selected as the experimental materials for friction stir lap welding. The emphasis is placed on the tensile strength, fracture location of the joint and the interface microstructure evolution of the weld under different welding heat inputs.

## Experimental

The base material was a 3 mm thick AC4C cast aluminum alloy plate and a 0.8 mm thick low carbon zinc-coated steel plate. The plate was cut and machined into rectangular welding samples, 300 mm long by 100 mm wide. They were longitudinally lap-welded with welding parameters of 1500 rpm rotational speed and 60-120 mm/min welding speed, using an FSW machine. The upsetting force of the welding tool (SKD61 tool steel) used in this experiment is 1 ton. The diameters of tool shoulder and tool pin are 15 mm and 5 mm, respectively. The length of the pin is 2.9 mm. The tilt angle of the tool is 3 degrees. After welding, the joint was cross-sectioned perpendicular to the welding direction for the metallographic analyses and tensile tests, using an electrical-discharge cutting machine. The cross-sections of the metallographic specimens were polished with diamond polishing agent, etched with Keller's reagent (1 ml hydrochloric acid, 1.5 ml nitric acid, 2.5 ml hydrofluoric acid and 95 ml water) and observed by optical microscopy. The mechanical properties of the joint were measured using tensile tests. Prior to the tensile tests, a micro-hardness tester was used to determine the fracture locations. The tensile tests were carried out at room temperature, at a crosshead speed of 1 mm/min, using a tensile testing machine. The mechanical properties were evaluated using three tensile specimens cutting from the same joint. The microstructure and element distribution in the lap interface were analyzed by scanning electron microscopy (SEM) equipped with an energy-dispersive X-ray (EDX) spectroscopy analysis system.

**Results and Discussion**

Fig.1 shows the microstructure of the base materials. AC4C base material is a hypoeutectic Al-Si alloy. Therefore, the base material presented a typical hypoeutectic structure. The steel base material showed ferritic structure due to low carbon content.

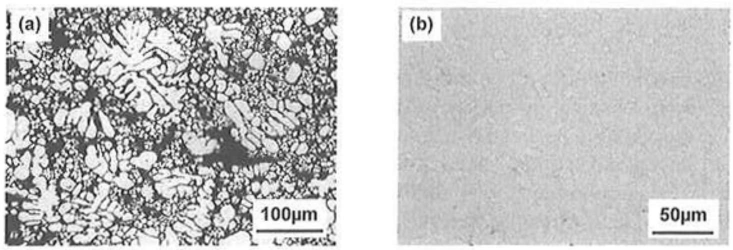


Fig.1: Microstructure of the base material; (a) AC4C aluminum alloy, (b) steel.

Fig.2 shows a typical transverse cross-section of a joint (100 mm/min) and the tensile test results. It can be seen from Fig.2a that the microstructure of the joint is significantly different from the surface to the interface of the joint. The details of the microstructural variations are demonstrated in Fig.3. Fig.2b shows the tensile strengths and fracture locations of joint in different welding speed. Experimental results show that the welding speeds have a significant effect on the tensile properties and fracture locations of the joints at the rotational speed of 1500 rpm. When the welding speed is higher than 60 mm/min, the joints fracture in the zinc-coated steel base material and the tensile strength is equal to that of the zinc-coated steel; when the welding speed is 60 mm/min, the joints fracture in the interface of the weld and the shear strength is about 50 MPa.

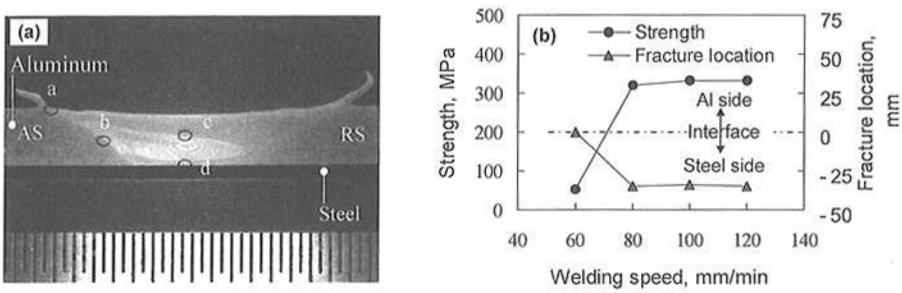


Fig.2: (a) Cross section of the joint (100 mm/min), (b) Tensile test results.

Fig.3a shows the microstructure near the surface of the joint. Compared with other aluminum alloy friction stir surface characteristic, the surface of AC4C aluminum alloy friction stir welding joint presents rough pattern. Fig.3b and 3c show the microstructure of the middle part of the joint. There is an obvious interface between stir zone (SZ) and thermal-mechanically affected zone (TMAZ). The microstructure in the former is significantly finer than that in the latter. Under the synthetic effect of the thermal cycle and the mechanical cycle, the materials in SZ have undergone the co-action of the high temperature action and severe plastic deformation during FSW. In this way, the original coarse primary aluminum grains and large eutectic silicon plates in the base material have been transformed to fine grains and small silicon particles, and such silicon particles are dispersed in the continuous fine grains aluminum matrix. Fig.3d shows the microstructure of the lap interface. It can be seen from this figure that there are large quantity intermetallic compounds (IMC) adjacent to the lap interface of the weld.

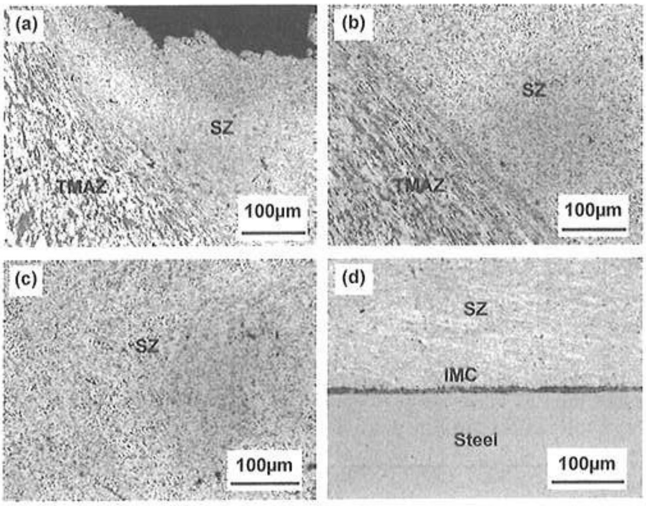


Fig.3: Microstructures in different regions shown in Fig.2a; (a) "a" region shown in Fig.2a, (b) "b" region shown in Fig.2a, (c) "c" region shown in Fig.2a, (d) "d" region shown in Fig.2a.

Fig.4 shows a typical microstructure of the interface in the lap joint and the relationship between the thickness of IMC and the welding parameters. It can be seen from Fig.4a that the joint consists of four layered structure; i-e, microstructure of Al alloy in SZ, IMC, zinc coat and base material of steel. That is to say, aluminum alloy and steel are joined through intermediate reaction zone. Therefore, the characteristics of distribution of IMC inevitably affect the mechanical properties of the lap joint. Fig.4b shows the relationship between the thickness of IMC and the welding parameters. The thickness of the IMC significantly increases from 7.7 μm to 58.1 μm with decreasing welding speeds from 120 mm/min to 60 mm/min. Lower welding speed means higher welding heat input and longer holding time. Especially, the reaction at interface can sufficiently carry out when lower welding speed is used, which leads to heavy thickness of IMC.

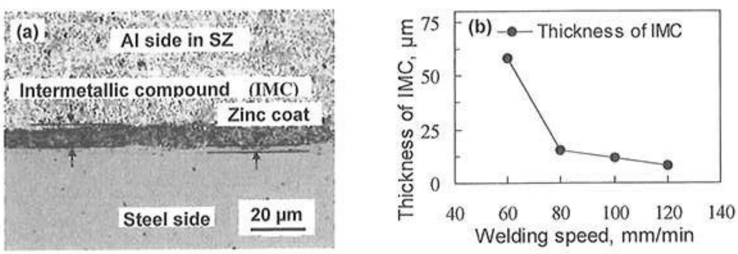


Fig.4: (a) A typical microstructure of the interface at welding speed of 100 mm/min, (b) Thickness of IMC changed with welding speeds.

In order to determine the IMC composition in the interface, line scanning and elements analysis on the interface structure were carried out. A layer involving Al, Fe, Zn and Si was formed at the interface of the joint, as shown in Fig.5. The elements analysis results of the Al-Fe-Si-Zn layer and the adjacent region are shown in Table 1. From these analysis results, and Fe-Al binary diagram and Fe-Al-Zn ternary diagram, the layer possibly consists of Al, Fe, Al-Fe or Al-Fe-Zn intermetallic compounds. The presence of large quantity of Si is possible due to the mixture of broken Si particles into the interface, during friction stir welding. In brief, the presence of the large thickness of IMC causes the shear fracture to take place at the interface during tensile test. The higher the welding input, the thicker the intermetallic compounds at the interface. On the other hand, aluminum alloy and steel are joined through intermediate reaction zone. Therefore, to obtain a sound lap joint, welding heat input has to be controlled.

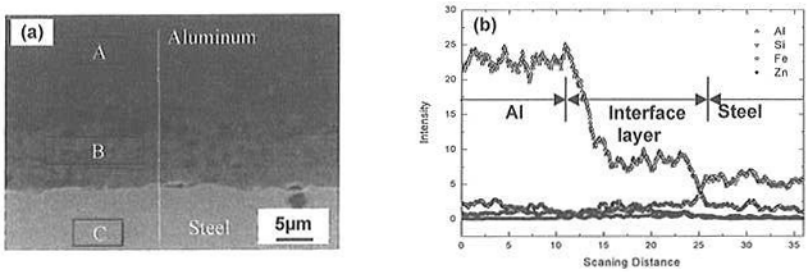


Fig.5: SEM image and the line analyses of interface structure; (a) SEM image and line scanning location, (b) line analyses of Al, Si, Fe and Zn.

| Position | Element ( mass% ) | | | |
|---|---|---|---|---|
| | Al | Fe | Zn | Si |
| A region | 78.86 | 8.38 | 1.15 | 11.62 |
| B region | 51.97 | 21.38 | 10.41 | 16.24 |
| C region | 14.84 | 83.38 | 0.6 | 1.18 |
| Original zinc coat | 1.59 | 20.28 | 78.13 | - |

Table 1: Elements analysis results at the interface and the adjacent regions.

**Summary**

The sound lap joint of AC4C cast aluminum alloy and zinc-coated steel was successfully obtained. The effect of welding speeds on the tensile properties and fracture locations of the joints was investigated, at rotational speed of 1500 rpm. When the welding speed is higher than 60 mm/min, the joints fracture in the zinc-coated steel base material and the tensile strength of the joint is equal to that of the zinc-coated steel; when the welding speed is lower than 60 mm/min, the joints fracture in the interface and the shear strength is about 50 MPa. The change of the fracture locations is attributed to the presence of large thickness of intermetallic compounds adjacent to the interface when the lower welding speed is used. Large thickness of intermetallic compounds increases brittleness of the lap joint, and leads to the shifting of the weak part of the joint from thin steel plate to the interface.

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