

Dissimilar Joining of Aluminum Alloy and Steel by Resistance Spot Welding

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ABSTRACT

This study concerns a dissimilar materials joining technique for aluminum (Al) alloys and steel for the purpose of reducing the vehicle body weight. The tough oxide layer on the Al alloy surface and the ability to control the Fe-Al intermetallic compound (IMC) thickness are issues that have so far complicated the joining of Al alloys and steel.

Removing the oxide layer has required a high heat input, resulting in the formation of a thick Fe-Al IMC layer at the joint interface, making it impossible to obtain satisfactory joint strength. To avoid that problem, we propose a unique joining concept that removes the oxide layer at low temperature by using the eutectic reaction between Al in the Al alloy and zinc (Zn) in the coating on galvanized steel (GI) and galvanized steel (GA). This makes it possible to form a thin, uniform Fe-Al IMC layer at the joint interface.

Welded joints of dissimilar materials require anticorrosion performance against electrochemical corrosion. A seal spot welding process is proposed here as a solution to that issue. Tests conducted on seal spot-welded joints showed that they provide both the required static tensile properties and anticorrosion performance. In addition to static tensile properties, seal spot-welded joints also satisfy all the other performance requirements for vehicle application, including fatigue

properties, high-speed tensile properties, low- and high-temperature tensile properties and anticorrosion performance. The seal spot welding process also has ample tolerance and excellent robustness against production variabilities such as the gaps between body panels and misalignment of the electrode angle.

INTRODUCTION

Reduction of fuel consumption and curbing carbon dioxide (CO₂) emissions are key issues being tackled by the automotive industry to resolve energy problems and the problem of global warming. Vigorous efforts are being made to develop technologies for improving powertrain efficiency⁽¹⁾ and for lightening the vehicle body⁽²⁾ as measures for addressing these issues.

Material substitution of aluminum alloys for steel is an effective way to reduce the vehicle body weight, and the establishment of effective techniques for joining Al alloys and steel has been strongly desired.⁽³⁻⁵⁾ One factor that governs the successful joining of dissimilar materials like Al alloys and steel is the strong oxide layer on the Al alloy surface. Removing that oxide layer requires a high heat input, which results in the formation of a thick Fe-Al intermetallic compound (IMC) layer at the joint interface. The formation of such a thick Fe-Al IMC layer lowers the joint strength and gives rise to the problem that a satisfactory joint between the two materials cannot be obtained.

A dissimilar materials joining technique has been desired that would overcome this problem by removing the oxide layer from the Al alloy surface at low temperature and allowing the formation of a thin, uniform Fe-Al IMC layer. As a possible solution to this issue, attention was focused in this study on zinc (Zn) that undergoes a eutectic reaction with Al at 382°C. It was proposed that this reaction be used to remove the oxide layer on the Al alloy surface at low temperature and thereby inhibit the formation of a thick Fe-Al IMC layer by reducing the heat input. An investigation was then made of this unique joining concept.

The proposed joining technique makes use of Zn in the coating on the galvanized steel sheet that is ordinarily used to manufacture vehicle body panels. Therefore, it does not lead to a cost increase because it does not require any new intermediate materials such as rivets or solder. Moreover, the resistance spot welding guns currently used for Al alloys can be diverted for this joining process without requiring any special modifications. Consequently, this joining technique does not require any new investment in facilities, making it advantageous with respect to cost considerations.

An investigation was made for improving the static tensile properties of the welded joint, which are among the characteristics required of vehicle body joints. Studies were also made of various other vehicle body performance requirements, including fatigue properties, high-speed tensile properties, low- and high-temperature tensile properties and anticorrosion performance. In addition, production requirements with respect to tolerance for variation in the gaps between body panels and misalignment of the electrode angle of the spot welding gun were also examined.

This paper describes the dissimilar materials joining technique that has been newly developed for Al alloys and steel. This technique provides a low-cost process that is applicable to production vehicles.

DISSIMILAR MATERIALS JOINING TECHNIQUE FOR AL ALLOYS AND STEEL USING THE AL-ZN EUTECTIC REACTION

Figure 1 shows the Al-Zn binary phase diagram. While the melting point of Al is 660°C and that of Zn is 419°C, the Al-Zn system undergoes a eutectic reaction at low temperature with an eutectic point at 382°C. Diffusion joining was used to conduct a fundamental study that focused on this phenomenon. The results showed that the Al-Zn eutectic reaction was effective for removing the oxide layer on the Al alloy surface.⁽⁶⁾ Industrial applications of diffusion joining have been limited so far to a narrow range of fields owing to the limitations of the process. Proceeding from the fundamental study, we

then developed a dissimilar materials joining process based on resistance spot welding, taking into account the requirements for application to production vehicles.

This process of joining dissimilar materials proceeds as shown in Fig. 2. An Al alloy and a galvanized steel sheet are placed one over the other and pressed together by applying the electrodes from above and below. When an electric current is passed, the contact resistance at the interface produces Joule heat that softens the materials. The oxide layer on the Al alloy surface is partially destroyed electrically and mechanically, allowing direct contact between Al in the Al alloy and Zn in the coating on the galvanized steel sheet. From that contact, a diffusion reaction occurs between the Al and Zn, and when the eutectic point is reached, a eutectic reaction occurs at low temperature in the near surface layers of the non-joined materials. The oxide layer on the Al alloy surface is enveloped by the eutectic melt and evacuated along with it from around the periphery of the joint area. As a result, that exposes the newly formed surfaces of both the Al alloy and the steel, bringing them into contact with one another. That produces a diffusion reaction between Fe-Al, making it possible to form a thin, uniform Fe-Al IMC layer.

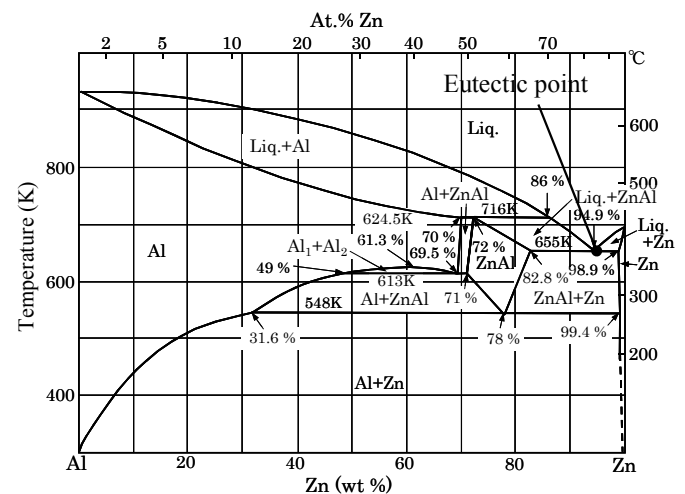


Fig. 1 Al-Zn binary phase diagram⁽⁷⁾

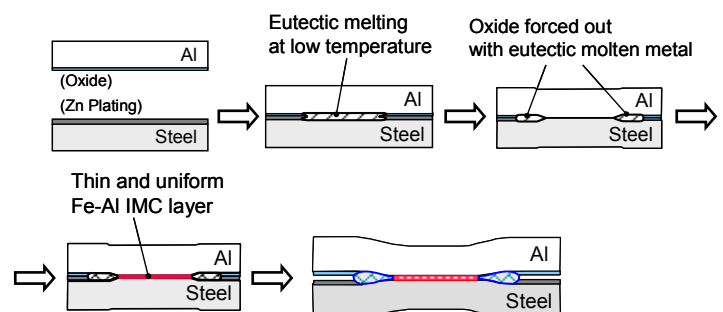


Fig. 2 Dissimilar materials joining process

A major issue for the actual use of this dissimilar materials joint between an Al alloy and steel is corrosion caused by the difference in the ionization tendency of Fe and Al. If moisture is present in the vicinity of such a dissimilar materials joint, electrochemical corrosion will develop, making it necessary to provide a sealing function that shuts out moisture.

For that purpose, we propose a seal spot welding process that provides both joint strength and anticorrosion performance. Seal spot welding is defined here as a process in which a sealant is placed between the two materials before they are joined together by spot welding. As a result, this joining process ensures anticorrosion performance by blocking the incursion of moisture into the interface between the dissimilar materials.

The process of forming a joint by seal spot welding proceeds as follows. Joule heat produced by the contact resistance at the initial joint interface causes the sealant to decompose. Residual sealant at the interface and the oxide layer on the Al alloy are enveloped by the eutectic melt and evacuated from around the periphery of the joint area. Subsequently, similar to the situation without any sealant, the joining process proceeds to form a thin, uniform Fe-Al IMC layer.

The structure of the joint formed by seal spot welding is shown in Fig. 3. The joint is structured such that the sealant blocks the incursion of moisture around the periphery of the joint, thereby securing both joint strength and anticorrosion performance.

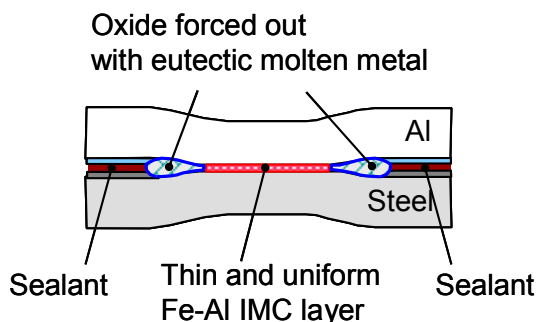


Fig. 3 Joint formed by seal spot welding

JOINING TESTS

Joining tests were conducted with resistance spot welding as the joining technique, using a portable spot welding gun for Al alloys. The resistance spot welding gun was fitted with upper and lower electrodes as the mechanism for applying pressure. It was assumed that this mechanism would be effective for evacuating the oxide layer, eutectic melt and sealant from around the periphery of the joint area.

Two types of zinc-coated steel sheet, i.e., galvanized steel (GI) and galvanized steel (GA), were used as the materials to be joined to a 6000-series Al alloy. A thermosetting epoxy resin was used as the sealant in the seal spot welding process.

The test pieces were prepared prior to welding in the following way. First, both types of steel were cleaned with ethanol using an ultrasonic cleaner. The Al alloy was polished with a stainless-steel headed grinder, in order to remove the oxide layer formed during mill production. After leaving the alloy in air for a few minutes to allow uniform formation of a new oxide layer, it was cleaned with ethanol.

JOINING TEST RESULTS

OBSERVATION OF JOINT INTERFACE - Figure 4 shows scanning electron microscope (SEM) images and line analyses by auger electron spectroscopy (AES) of the interface of the joint formed with the proposed joining technique, for a combination of the GI steel and 6000-series Al alloy. These observation results confirmed that a thin, uniform Fe-Al IMC layer can be formed with this process as a result of enveloping the oxide layer on the Al alloy surface in the eutectic melt and effectively evacuating it from around the periphery of the joint area. A similar SEM observation confirmed that this joining technique achieved the same effect when it was applied to a combination of the GA steel and 6000-series Al alloy.

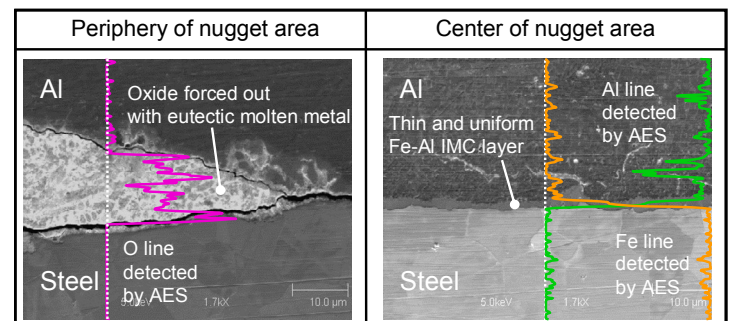


Fig. 4 Cross section of joint interface

STATIC TENSILE PROPERTIES - Static tensile properties were evaluated in terms of tensile shear strength (TSS) and cross tensile strength (CTS). These tensile strength properties were found using test pieces and test procedures complying with JIS Z3136 and JIS Z3137, respectively. The test pieces were made of the GA steel (plate thickness: 0.55 mm) as the material to be joined to the 6000-series Al alloy (plate thickness: 1.0 mm). Because an epoxy resin was used as the sealant in this study, the thermosetting of the sealant around the periphery of the joint would contribute to joint strength.