Development of aluminum alloy/galvanized steel joining method using refill friction stir spot welding

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ABSTRACT
Friction stir spot welding (FSSW) is one of the solid-state welding method and dissimilar material joining by FSSW has been investigated. However, a removable coating is required to form a clean surface on the lower plate in conventional FSSW method. Therefore, we have developed a new dissimilar material joining method – scrubbing refill FSSW (Sc-RFSSW) – and Sc-RFSSW provides higher joint strength than conventional FSSW methods in joining the aluminum alloy and non-coated mild steel. In this study, the mechanical properties and metallurgical joining interface of an aluminum alloy and a hot-dip galvanized (GI) coated steel joint by Sc-RFSSW were investigated. In addition, a new tool tip shape was examined to improve the interfacial cleaning effect.

KEYWORDS
Dissimilar metal joining; friction stir spot welding; refill friction stir spot welding; joint strength; galvanized steel

1. Introduction
In recent years, the automobile industry has been strongly required to improve fuel efficiency against the backdrop of CO₂ emission regulations in Europe and other countries, and there has been active development of multi-material bodies to reduce body weight and Evs [1–3]. Mechanical fastening methods such as Self Piercing Riveting [4–6] and Mechanical clinching [7,8] are mainly used in the manufacture of multi-material bodies for automobile bodies, however, riveting increases cost and weight. The development of a metallurgical joining method is desired. Friction Stir Spot Welding (FSSW) is one of the methods for metallurgically joining dissimilar metals, and recently, refill FSSW has been developed to obtain a smooth appearance. As shown in Figure 1, the main feature of the refill FSSW is that the pin located at the center of the tool and the shoulder around its periphery are composed of separate parts. This independent action of the pin and shoulder, respectively, with respect to the direction of the pressurization axis, allows keyholes created in the joint to be backfilled in the process. Generally, in the joining of dissimilar metals in FSSW and refill FSSW, the rotating tool is press-fitted into the upper plate only, and the material flow in the upper plate forms the newborn surface of the lower plate. Metallurgical joining is then performed by applying heat to the new surfaces of dissimilar metals while bringing them into contact with each other [9–12].

Metallurgical joining is achieved by applying heat input [9–12]. However, the method of forming a new surface on the lower plate by the material flow of the upper plate is easily affected by the surface condition of the lower plate, and it has been reported that the joint strength decreases when the lower plate is non-coated steel or galvanized alloyed (GA) steel [13]. To solve these problems, the author developed Scrubbing refill FSSW as a new dissimilar metal joining method using refill FSSW [14]. The development concept of this method is to obtain a high interface cleaning effect in a short time, assuming its application in automobile assembly lines. Specifically, as shown in Figure 2, the tool press-in process is characterized by bringing the shoulder into contact with the lower plate, with the aim of actively forming a new surface of the lower plate with a tool made of tungsten carbide. The refilling process also prevents through holes in the upper plate and
improves corrosion resistance. In a previous study [14] that examined the joining of aluminum alloy/non-coated mild steel, it was confirmed that plug fracture was stably obtained in aluminum alloy sheets in both tensile shear strength (TSS) and cross tensile strength (CTS) tests in a joining time of less than 2 s, and it was also confirmed that the plug fracture was higher than in conventional FSSW and refill FSSW. The results showed that joint strength could be obtained.

It was also confirmed that a very thin amorphous layer of 4–6 nm was formed at the welding interface, indicating that aluminum alloy/non-coated mild steel joints with high interfacial strength can be fabricated by using the scrubbing RFSSW. Similar studies include FSSW [15], which performs material refilling in multiple joining processes, and FSSW [16], in which double-action tools are placed on both the upper and lower surfaces, has been performed, and it has been reported that good joint strength has been obtained for joining aluminum alloy/non-coated mild steel.

On the other hand, the effect of coating on steel plates in this type of refill FSSW dissimilar-material joining with plastic deformation of the lower plate has not yet been clarified. Since most automotive steel sheets are zinc coated for corrosion protection, it is important to understand the effect of coating on joint strength and dissimilar metal interfaces [17]. In this paper, we focus on hot-dip galvanizing (GI) because we believe it is important to clarify the behavior of coating ejection due to tool contact during joining. GA coating consists of a pure Zn layer and a Fe-Zn alloying layer, while GI coating consists of a pure Zn layer only. Therefore, in the case of aluminum alloy/GI-coated steel joints, the amount of Zn residue at the joint interface can be used to discuss coating emissions. Therefore, in this study, aluminum alloy/GI coated steel joints were fabricated by Scrubbing refill FSSW to investigate joint strength and coating removal from the interface. In addition, since the new surface is formed by direct contact between the tool and the steel in this method, we investigated the improvement of coating ejection by changing the tool tip geometry.

2. Experimental method

A6061-T6 aluminum alloy plate (1.0 mmt) was used for the upper plate and GI-coated mild steel plate (1.2 mmt) for the lower plate as specimens. Table 1 shows the composition and mechanical properties of the five major elements in A6061-T6 aluminum alloy sheet and GI-coated mild steel sheet. The coating thickness of the GI coated steel sheet used was approximately 22 μm.
A refill FSSW apparatus manufactured by Kawasaki Heavy Industries was used for the joining tests, and tungsten carbide tools with a shoulder diameter of $\varnothing 8$ mm and a pin diameter of $\varnothing 4.5$ mm were used. Joining was performed by position control. The rotational speed was set to 2000 rpm, the pressurization was 13 kN in the press-in process, the refilling process was 9 kN, and the target tool plunging depth was 1.02 mm from the upper plate surface. As shown in Figure 1, the refill FSSW has a clamping mechanism on the outer circumference of the joining tool to prevent material leakage. In this study, 5 kN of the set pressure was used as clamping pressure around the hitting point. Tensile tests were conducted to investigate the mechanical properties of the joints. The crosshead speed is 10 mm/min for normal tensile tests, and 1 mm/min for unloading tests where the test is stopped in the middle of a tensile test to observe the joint condition at each load, in order to stop the test at an arbitrary point. Scanning electron microscopy (SEM) was used to analyze the macrostructure and microstructure of the joint cross section, and energy dispersive X-ray spectroscopy (EDS) was used to investigate the distribution of the component composition at the interface. In addition, a stop-action test was conducted to interrupt the process in order to clarify the interface conditions between the upper and lower plates during joining. In order to investigate the newborn surface formation immediately after the press-in process, the tool was forcibly pulled out at the moment of transition from the press-in process to the refilling process, interrupting the process.

3. Experimental results and discussion

3.1. Relationship between tool holding time and coating discharge

Figure 3 shows the strength evaluation results of the aluminum alloy/galvanized steel sheet joint. In order to investigate the relationship between tool/substrate contact time and galvanizing ejection, a process to maintain tool/substrate contact was added immediately after the press-fit process. For comparison, the joint strength of aluminum alloy/non-coated steel joints [14] obtained in a previous study is also shown in the figure, and the holding time, in this case, is 0 s. First, at a holding time of 0 s, the joint strength is significantly lower than that of the aluminum alloy/non-coated steel joint. Figure 4 shows the EDS results of the Zn ratio of the junction interface composition in the radial direction from the center of the junction, and it is clear that a large amount of Zn reaction was observed almost everywhere in the junction area at a holding time of 0 s. This indicates that the zinc coating was not discharged sufficiently, and the decrease in joint strength at a holding time of 0 s is assumed to be due to insufficient zinc coating discharge.

Next, when the contact time between the tool and the bottom plate was set, it was found that both TSS and CTS tended to improve after a holding time of 1 s, while the maximum CTS was obtained at a holding time of 2 s. Furthermore, Figure 4 shows that the Zn reaction at the interface was significantly reduced under all conditions with retention time. Therefore, it is clear that the holding time significantly improves zinc coating discharge.

As an example of the joint cross-section obtained in this case, Figure 5 shows a photograph of the cross-section of a joint in the 0-s holding time condition and in the 2-s holding condition.
time condition in which the maximum CTS was obtained. The EDS positions in Figure 4 are shown in the figure for reference. At a holding time of 0 s, the lower plate maintains a smooth shape, but at a joint with a holding time of 2 s, plastic flow of the steel occurs, and the lower plate is greatly deformed along the shoulder contact area.

This is thought to be due to the fact that the holding time control maintains the processing conditions, such as the number of revolutions and pressurization, and does not maintain the tool position, resulting in increased softening of the steel sheet and larger deformation as the joining time increases. SEM observation of the area corresponding to the outer circumference of the shoulder in the joint with a holding time of 2 s revealed a periodic flow layer (Figure 6). The fluidized bed is known from EDS analysis to be an Al-Fe-Zn compound and is assumed to have been formed by the stirring of the upper and lower plates. This layered structure

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**Figure 4.** Relationship between holding time and Zn concentration distribution at joint interface.
of strongly stirred dissimilar metals is often observed in friction stir welding (FSW) [18,19]. It has been reported that this is especially likely to occur when the tool contacts the lower plate and that the metallurgical reaction is promoted by the mixing of the upper and lower plates, as well as the tendency for crack propagation in this layered structure [20].

In terms of the fracture mode of the joints, most of the TSS joints with a holding time of 2 s had plug fractures that propagated cracks in the aluminum, while all the CTS joints had partial plug fractures. Figure 7 shows a typical example of a plug fracture in TSS and a partial plug fracture in CTS. Partial plug fracture here refers to interface rupture in the area just below the shoulder and plug fracture in the area just below the pin. In order to observe crack propagation in CTS joints, unloading tests were conducted in which the test was stopped in the middle of the tensile test to observe the condition of the joint at each load. The points where the test was stopped are indicated by arrows in Figure 8.

The results of the unloading test shown in Figure 8 indicate that the cracks initiated at the outer circumference of the joint before reaching the maximum strength, indicating that the cracks propagated in the cyclic flow regime described above. Therefore, the outermost circumference of the joint does not contribute to the maximum strength of the joint, and it is assumed that the actual diameter of the joint was reduced. The periodic fluidized bed may be a sufficient indicator of fusion in FSW, but in this joint, the fluidized bed reaches more than 20 μm in thick sections, which may have been a crack propagation path. It has been reported that it is desirable to form intermetallic compounds at the aluminum/steel dissimilar metal interface as thin as 1 μm or less [21,22], and it is important to reduce the thickness of the compound layer in order to improve joint strength.

In order to investigate the factors that lead to the formation of the periodic flow layer shown in Figures 6 and 8(b), a stop-action test was conducted in which the process was interrupted during joining, and the results are shown in
The process was interrupted just before the refilling process and the tool was pulled out instantaneously under both the 0 and 2 s holding time conditions. The shape of the lower plate at both 0 and 2 s of holding time is approximately the same at the time of stop action and at the time of joint completion, and the condition of the backfill material in the upper plate differs significantly. Therefore, it can be said that the stop-action joint is not affected by the material flow during refilling, but only by the plastic flow results of the tool press-fitting and holding processes. SEM observation of the interface in the white frame of the joint cross-sectional photograph revealed that a periodic flow layer was hardly observed at a holding time of 0 s, whereas a periodic and coarse flow layer was observed at a holding time of 2 s. The SEM observation of the interface in the white frame of the joint cross-sectional photograph revealed that a periodic and coarse flow layer was observed at a holding time of 2 s.

Therefore, it was confirmed that the stirring of the upper and lower plates by the tool increases with increasing contact time between the tool and the lower plate, and the periodic flow area expands. Based on the above results, the next section discusses a tool geometry that can sufficiently discharge galvanization even
when the tool/substrate contact time is short, with the aim of reducing the thickness of the fluidized bed.

### 3.2. Improvement by tool tip shape

In order to discharge the zinc coating quickly, a tapered shape on the normally smooth shoulder end face was considered. In this study, three types of taper tool were prepared with the taper tip position on the inner shoulder side (Tool I), the center of the shoulder thickness (Tool C), and the outer shoulder side (Tool O). A photograph of each tool is shown in Figure 10. The taper height of each tool was 0.2 mm. A cross-sectional photograph of the joint using the taper tool is shown in Figure 11, and it was observed that the lower plate was deformed along the taper shape by both tools. Therefore, it is suggested that the taper has a certain effect on the plastic flow on the lower plate surface. Since no retention process is provided for any of the joints, the retention time corresponds to the 0-s condition. One feature of the joint shape is that the upper plate is also backfilled along the taper shape.

Tool I, which has a tapered tip position on the inside, reduces the step on the upper plate surface, resulting in a smooth shape, which is expected to improve the strength at plug fracture, when a crack propagates through the upper plate, and to improve the electrodeposition coating and corrosion properties of the joint edge.

Figure 12 shows the strength evaluation results for each joint. Strength improvement was observed for Tool I, which has a tapered tip position on the inside, and Tool O, which has a tapered tip position on the outside, but the strength properties of Tool C, which has a tip position at the center of the wall thickness, were equivalent to those of the conventional tool. In particular, joint properties equivalent to a holding time of 2 s without holding time were obtained for Tool I, and it was confirmed that the highest strength improvement effect was obtained when the tapered tip position was provided on the inside.
Next, the results of the observation of the microstructure near the interface using Tool I, Tool C, and Tool O are shown in Figure 13. In Tool I, it was observed that the periodic flow area at the interface was greatly reduced in addition to the sufficient removal of zinc coating from the interface. The flow area formed by the conventional tool with a thickness of 20 μm or more (Figure 6) was suppressed to a maximum thickness of about 7 μm at the same observation position, and areas with a thickness of 1 μm or less were also observed. Therefore, it was confirmed that the tapered shape of the shoulder tip provides sufficient zinc coating discharge even when the tool contact time is short, and in addition, the shortened tool contact time suppresses the periodic flow area at the interface. On the other hand, a Zn-rich compound layer was observed at the outer circumference of the joint in the Tool C joint, which had low joint strength, and this was thought to be a solidified layer where the liquid phase generated by the melting of Al-Zn eutectic was retained [11]. In addition, cracks were observed along the surface of the Zn-rich compound layer, suggesting that this coarse compound layer was a factor in the strength reduction. In Tool C, the tool tip is bent, so the gap between the tool and the bottom plate during refilling is also bent, and the flowability of the top plate material was inhibited, which is thought to have caused the galvanization to be retained easily. Therefore, a lower taper height is expected to be desirable in the Tool C shape. However, cracks were observed on the steel plate side at the edge of the joint because the outer circumference of the joint was the area where the largest plastic flow occurred.

These results indicate that Tool I is the best in terms of both galvanization discharge and fluidized bed suppression at the joint ends and that the highest joint strength was obtained with Tool I among the three types of tapered shapes. Therefore, the tapered shape of the tool tip is effective in improving the joinability of aluminum alloy/galvanized steel joints, and the tapered tip on the inner diameter side of the shoulder is preferable.

However, it is clear that sufficient CTS has not yet been obtained, and that coarse compound layers may be generated depending on the tool geometry. In the future, we plan to optimize the shape of the taper tool to ensure joint strength equivalent to that of aluminum alloy/non-coated steel joints in aluminum alloy/galvanized steel joints.

4. Concluding remarks

This paper reports on the strength properties of aluminum alloy/galvanized (GI) steel joints fabricated by the Scrubbing refill FSSW. In aluminum alloy/galvanized (GI) steel joints, a periodic flow layer may form at the interface, and if this flow layer is thick, the strength of the joint is reduced. It was also found that there is a correlation between tool/substrate contact time and fluidized bed formation.

We proposed a tapered tool with a tapered shoulder tip to reduce the thickness of the fluidized bed and showed that a tapered tip position on the inside of the shoulder is desirable.

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References

[1] Hambrecht T, Alber U. The new Audi Q7. Bad Nauheim: EuroCarBody; 2015.

[2] Kawai K. Trends of multi-materialization and required technologies in the future. Tokyo: Reed Exhibition Japan Ltd.; 2019.

[3] Kambe H. Vehicle weight reduction and application of aluminum alloy casting technology. Tokyo: Reed Exhibition Japan Ltd., 2019.

[4] Barnes TA, Pashby IR. Joining techniques for aluminium spaceframes used in automobiles: part II—adhesive bonding and mechanical fasteners. J Mater Process Technol. 2000;99(1–3):72–79.

[5] Michalos G, Makris S, Papakostas N, et al. Automotive assembly technologies review: challenges and outlook for a flexible and adaptive approach. CIRP J Manuf Sci Technol. 2010;2(2):81–91.

[6] Abe Y, Kato T, Mori K. Self-piercing riveting of high tensile strength steel and aluminium alloy sheets using conventional rivet and die. J Mater Process Technol. 2009;209(8):3914–3922.

[7] Varis JP. The suitability of round clinching tools for high strength structural steel. Thin-Walled Structures. 2002;40(3):225–238.

[8] Nong N, Keju O, Yu Z, et al. Research on press joining technology for automotive metallic sheets. J Mater Process Technol. 2003;137(1–3):159–163.

[9] Shoji Y, Takase K, Gendo T, et al. Development of spot friction welding technology of aluminium alloy and steel. Mazda Technical Report 2006. 2006:24.

[10] Fukada S, Ohashi R, Fujimoto M. Okada: refill friction stir spot welding of dissimilar materials consisting of A6061 and hot dip zinc-coated steel sheets. In Proceedings of the 1st international joint symposium on joining and welding. Amsterdam: Elsevier; 2013. p. 183–187.

[11] Suhuddin UFH, Fischer V, Kostka A, et al. Microstructure evolution in refill friction stir spot weld of a dissimilar Al-Mg alloy to Zn-coated steel. Sci Technol Weld Joining. 2017;22(8):658–665.

[12] Dong H, Chen S, Song Y, et al. Refilled friction stir spot welding of aluminum alloy to galvanized steel sheets. Mater Des. 2016;94:457–466.

[13] Ohashi R. Dissimilar material joining by FSSW. J Japan Weld Soci. 2018;87(1):28–32.

[14] Takeoka N, Tsuchida T, Matsuda T, et al. Analysis of mechanical properties and interfacial layer – development of a new dissimilar material joining method using refill friction stir spot welding (1st. Prepr Natl Meet JWS. 2021;109:104–105.

[15] Sun YF, Fujii H, Takaki N, et al. Microstructure and mechanical properties of dissimilar Al alloy/steel joints prepared by a flat spot friction stir welding technique. Mater Des. 2013;47:350–357.

[16] Wang X, Morisada Y, Fujii H. High-strength Fe/Al dissimilar joint with uniform nanometer-sized intermetallic compound layer and mechanical interlock formed by adjustable probes during double-sided friction stir spot welding. Mater Sci Eng A. 2021;809:138710–138743.

[17] Kimapong K, Watanabe Lap T. Joint of A5083 aluminum alloy and SS400 steel by friction stir welding. Mater Sci Technol 2005;46(4):835–841.

[18] Watanabe M, Ookawa T, Kumai S. Formation of laminate structure at the friction stir weld interface of aluminum alloy/steel lap joint. J Japan Inst Light Metals. 2007;57(11):536–554.

[19] Movahedi M, Kokabi AH, Reihani SMS, et al. Effect of tool travel and rotation speeds on weld zone defects and joint strength of aluminium steel lap joints made by friction stir welding. Sci Technol Weld Joining. 2012;17(2):162–167.

[21] Hirose A, Matsui F, Imaeda H, et al. Interfacial reaction and strength of dissimilar joints of aluminum alloys to steels for automobile. MSF. 2005;475–479:349–352.

[22] Ogura T, Hirose A. Microstructural control of interface and mechanical properties in dissimilar metal joining between aluminum alloy and steel. J Japan Inst Light Metals. 2016;66(9):503–511.