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Fatigue Behavior of Dissimilar Al Alloy/Galvanized Steel Friction Stir Spot Welds Fabricated by Scroll Grooved Tool without Probe

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Abstract: In this study, the tensile-shear fatigue tests were performed to investigate the effect of plated zinc layer to the fatigue strength of dissimilar FSSW joint. The Aluminum alloy and galvanized steel are successfully joined by the FSSW technique. FSW scroll grooved tool was used and inserted only into aluminum plate. The tensile-shear strength and fatigue strength of the joint are 3300N and 1250N, respectively. Both of the static and fatigue fracture were interface fracture mode. Detailed observation of the plated zinc layer characteristic using a scanning electron microscope (SEM) with energy dispersive X-ray spectroscopy (EDS) shows that the interface layer was formed between the aluminum alloy surface and steel surface. The EDS analysis of this new formed interface layer was compromised of Fe and Al elements, while the zinc was not detected by the EDS analysis. These indicate that during the FSSW process, the plated zinc layer was melted and has been peeled off from the base steel surface. As the result, the melted plated zinc layer was squeezed out from the joint area by the plastic flow of the Al alloy. Then, this melted plated zinc layer was cumulative at the weld periphery forming a new layer coating surrounding the FSSW joint which is providing the FSSW joint a stress relaxation at the weld notch enhancing the joint strength.

Key words: *Fatigue, Friction Stir Spot Welding, Dissimilar weld, Aluminum alloy, Galvanized steel*

1. INTRODUCTION

The efforts among the automobile manufacturer in reducing the vehicle weights due to the demanding for better fuel consumptions while maintaining the high strength to weight ratio have lead the increasing of the aluminum [1], meanwhile the steel is also used as used to be because of its high reliability. Therefore the dissimilar weld of Al/Fe is required in the manufacturing sector in order to achieve this goal.

The weld ability of dissimilar material has been well explored in conventional fusion bonding, such as resistantance spot welding, laser welding and etc. A large temperature difference between types of metal used in the dissimilar weld may cause mechanical property degrading due to melting and re-solidification during the welding process.

Furthermore, intermetallic compounds can easily be formed at the interface between the dissimilar metal in conventional fusion bonding, where this cannot secure a sufficient strength of the joint because of brittle fracture mechanism of the intermetallic compound itself. Since the formation of the intermetallic compound can be controlled in the solid bonding phase as the FSSW methods[2], it is possible to avoid the brittle fracture of dissimilar weld.

Recently a number of researches have been made so far for dissimilar between aluminum alloy and galvanized steel by using friction stir spot welding (FSSW). The result shows that the plated zinc layer has improved the static fracture strength of dissimilar weld.[3] However, the joint between dissimilar metals is used in general structure, it is necessary to understand the fatigue behavior of the dissimilar welds interface , but detailed research on the interface fatigue of the dissimilar FSSW joint has not yet been investigated.

In this study, the dissimilar lap welds between aluminum alloy sheet and galvanized steel sheet were fabricated by FSSW method using a scroll grooved tool without probe and tensile shear fatigue tests were conducted. The fatigue strengths of these joining were evaluated and fracture mechanisms were discussed based on microstructure analysis of the weld zone.

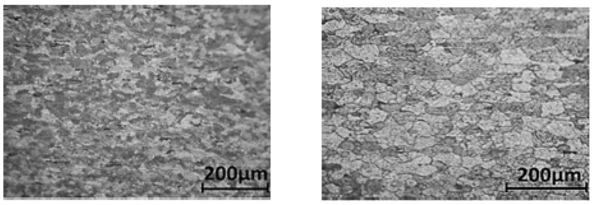
2. EXPERIMENTAL DETAILS

2.1 Materials and Specimen Configuration

As base material, an automotive standard used material SGCA galvanized steel and A6022 aluminum alloy were used for the FSSW joining, whose thickness of each sheet are 1.4mm and 2.0 mm, respectively. The chemical compositions of the base material and plated zinc layer were summarized in Table 1.

The microstructures of the SGCA and A6022 on the cross-section are revealed in Fig. 1. Fig. 2 shows the plated zinc layer thickness is almost 8 μm.

The dissimilar FSSW joint strength was evaluated by using tensile-shear lap specimen. The dimensions of the specimens are according to JIS. Specimen were made by using two sheets 40mm×150mm sheets with a 40mm×40mm overlap area as shown in Fig. 3. The upper and lower sheets are aluminum alloy and galvanized steel, respectively.



(a) (b)

Fig. 1 Microstructures of materials on the cross-section (a) SGCA270C, (b) A6022-T4

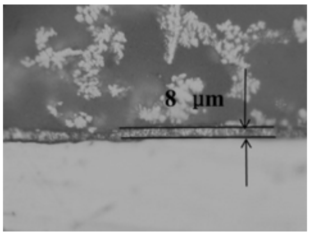


Fig.2 Thickness of the plated zinc layer

Table 1 Chemical composition of materials (mass %)

	Si	Fe	Mn	Mg	Zn	Ti	Al
A6022	1	0.15	0.07	0.56	0.01	0.02	Bal

	C	Si	Mn	P	S	Fe
SGCA270	0.01	0.01	0.16	0.13	0.06	Bal

	Fe	Al	Zn
Plated zinc layer	9-11	0.2-0.3	Bal

2.2 Tool Geometry and Welding Conditions

The scroll grooved tool without probe is shown in Fig.4 where it’s performance is describe in the work Tozaki *et al* [4].

The aluminum alloy and galvanized steel sheets were overlap and tightly clapped. The dissimilar weld tensile-shear and fatigue test specimens were spot lap joint using automated friction welding machine

In the FSSW, the important processing variables are tool rotational speed, tool holding time, and tool plunge depth. It should be noted that the tool has no probe, but a 0.5 mm depth scroll grooved on its shoulder surface. Therefore, the insertion depth of the shoulder part was defined as the tool plunge depth.

In this study, pre-tensile test were conducted to define those variables and fixed as the tool rotational speed of 3000 rpm, the tool holding time of 5 s and the shoulder plunge depth of 0.7 mm. In all specimens, the tool was inserted from the Al alloy sheet side. Then the rotating tool was reacted from the Al alloy side and left the joint cool by air.

2.3 Experimental Procedures

The joint mechanical properties were evaluated using harness test, tensile-shear test and fatigue test. After the welding the specimen was cut as such as cross-section is perpendicular to the welding direction for Vickers hardness test under load 4.9 N with dwell time for 30 s. The interface structure and element distribution of the joint were analyzed using scanning electron microscopy (SEM) equipped with energy dispersive X-ray spectroscopy (EDS) analysis system.

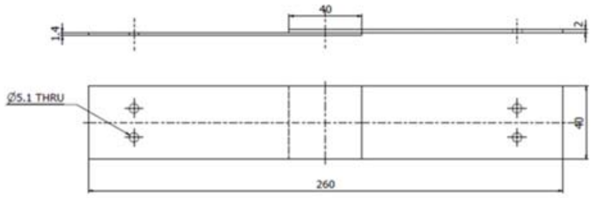
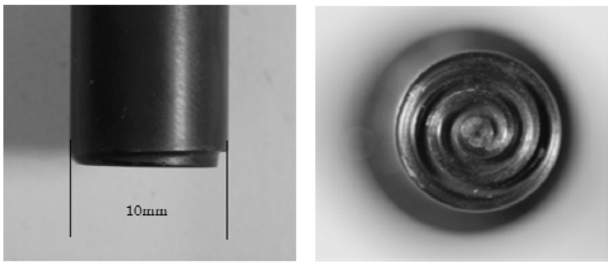


Fig. 3 Lap shear specimen configuration.



(a) (b)

Fig. 4 The scroll design tool;[5]
(a) side view, (b) bottom view

The fatigue tests were conducted with an electro-hydraulic fatigue testing machine under load control at room temperature and different loading amplitudes. The test operating at a sinusoidal frequency of 10 Hz and stress ratio of R = 0.1.

After fatigue tests, the fracture surfaces were analyzed in detail using scanning electron microscopy (SEM) equipped with energy dispersive X-ray spectroscopy (EDS).

3. EXPERIMENTAL RESULT

3.1 Microstructure in the Weld Zone

After the FSSW process, a detail examination was made on the vertical cross-section of the FSSW dissimilar weld. The macroscopic view of the vertical cross-section of the FSSW dissimilar weld is shown in Fig. 5.

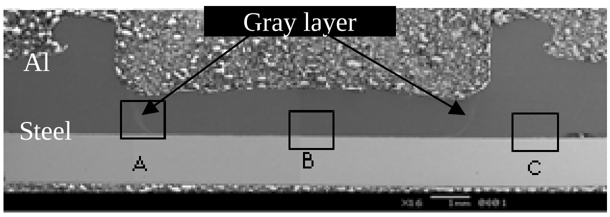


Fig. 5 Macroscopic appearance of the cross-section of the weld zone

The upper side is the Al alloy sheet and the lower side is the steel sheet side. The interface between the upper and lower sheet is clearly been seen which indicates that stirring of material occurred only in the upper sheet, A6022. The microstructures of the weld zone are similar to as reported by Uemastu et al[5].

The EDS line analysis revealed the presence of Al and Fe across the interface layer, which indicates that the intermetallic compound (IMC) layer was formed at the Al/Fe interface during FSSW but the presence of zinc was not detected as shown in the corresponding EDS line analysis of the image in Fig. 6.

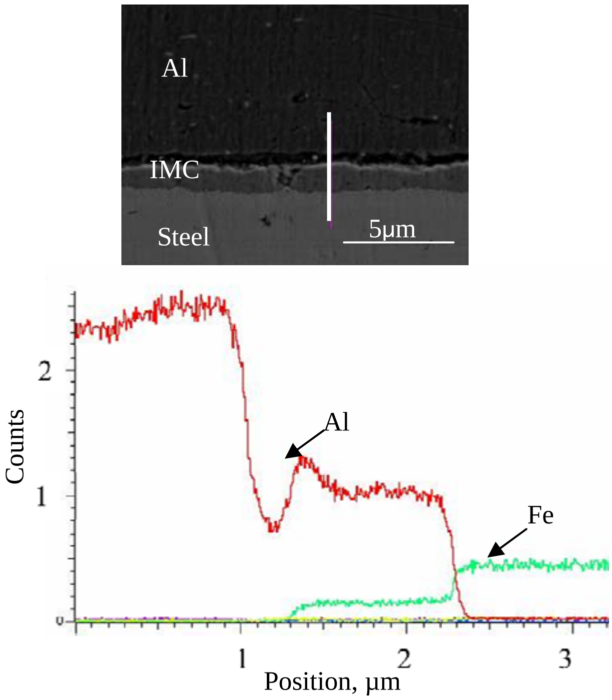


Fig. 6 EDS line analysis of the interface

In order to observe and understand the plated zinc layer flow behavior during the FSSW process, a higher magnification and EDS analysis of the interface at region A, B, and C in Fig. 5 are shown in Fig. 7. During the FSSW process the interface temperature rises up until 430℃ [3] and the plated zinc layer are melted at the joint interface. While the stirring process removed the melted zinc from the steel surface and leaving a newly fresh steel surface and allowing an interface layer forming, consist of Fe and Al elements, as shown in Fig. 7 (B).

Further observation, the melted plated zinc layer were squeezed out to the periphery region of the FSSW joint due to the plastic flow of the Al alloy during the FSSW process, as shown in Fig. 7. A symmetrical gray layer pattern which is rises up from the joint interface toward the Al sheets near the weld periphery. This layer is consisting of zinc, as shown in Fig. 7 (A). Figure 7 (C) shows this melted plated zinc layer were solidified at the weld periphery forming a new layer coating surrounding the FSSW joint which providing the FSSW joint a geometry effect at the weld notch .

3.2 Vickers Hardness Distribution

The hardness distributions of the dissimilar welds were measured along the line ± 0.01mm from the interface and it is measured from the center of the joint with ±10mm range. The Vickers hardness distributions of weld zone are shown in Fig. 8. The hardness distribution in the stir zone on the al-side is similar to the base metal (*HV* 78) but the Vickers hardness on TMAZ is reducing due to the dissolution of fine precipitations in the Al sheet. In despite, the hardness distribution in the stir zone on the steel side is higher than the base metal (*HV* 120) due to work hardening induced by the stirring heat during the FSSW process.

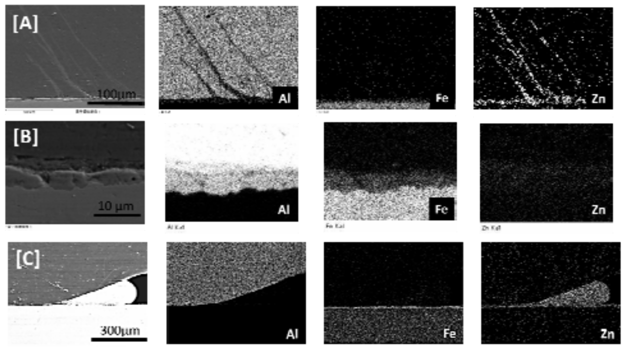


Fig. 7 EDS analysis of the cross-section of the weld zone : (A) gray layer, (B) center, (C) weld periphery in Fig. 5, respectively.

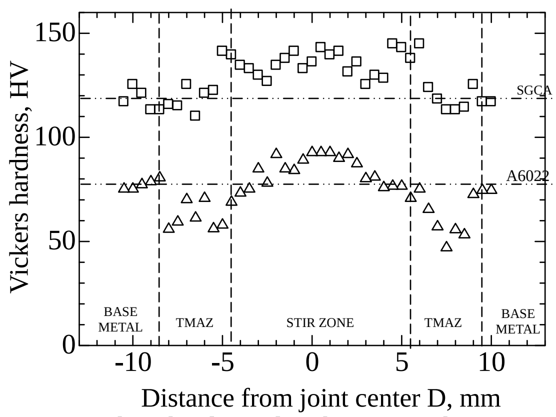


Fig. 8 Vickers hardness distributions in the cross-section of weld zone.

3.2 Tensile-Shear Strength under Static Loading

The average tensile-shear strengths of three specimens in the dissimilar are 3.3 kN. Typical macroscopic appearances of tensile-shear fracture surface of dissimilar welds are shown in Fig. 9. The static loading fracture surface was observed in order to evaluate the static fracture mechanism. It is appeared that the fracture occurred along the interface layer.

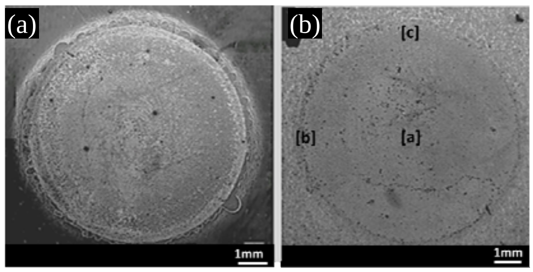


Fig. 9 SEM macrographs showing tensile-shear fracture surface of dissimilar FSSW joint: (a) Al side (b) steel side

A detail observation on the tensile-shear fracture surface is conducted using an EDS analysis. The results of EDS on analysis of region (a), (b) and (c) in Fig. 9 are shown in Fig. 10. Al adhesive was observed on almost the entire joint fracture surface. In the meantime, zinc was not found at the center of the joint fracture surface but only at the periphery region, as shown in Fig. 10 (b) and Fig. 10 (c).

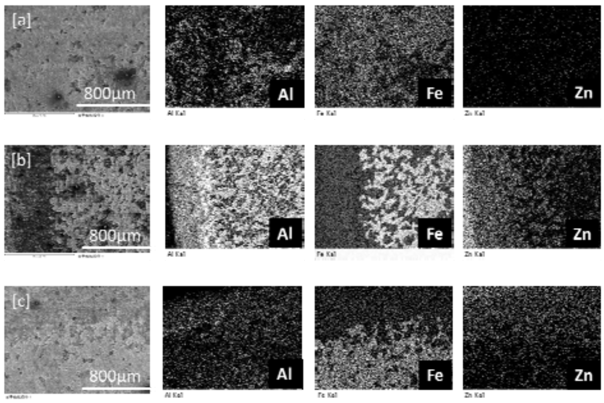


Fig. 10 EDS analysis of the tensile-shear fracture surface: (a) Center, (b) left, and (c) top side in Fig. 9, respectively.

3.4 Tensile-Shear Strength under Fatigue Loading

The fatigue test results of the dissimilar FSSW for Al-SGCA is shown in Fig. 11. As a reference, A6061-SPCC fatigue test result by Uematsu *et al*[5] is also plotted. The fatigue strengths of the dissimilar welds of Al-SGCA are higher than those welds of A6061-SPCC despite that the tensile-shear strength of A6061-SPCC is 5.4kN as report by Uematsu *et al* which is higher than that of A6022-SGCA dissimilar weld. The fatigue strengths of A6022-SGCA dissimilar weld is at 1250N where all the fractures are interface fracture mode.

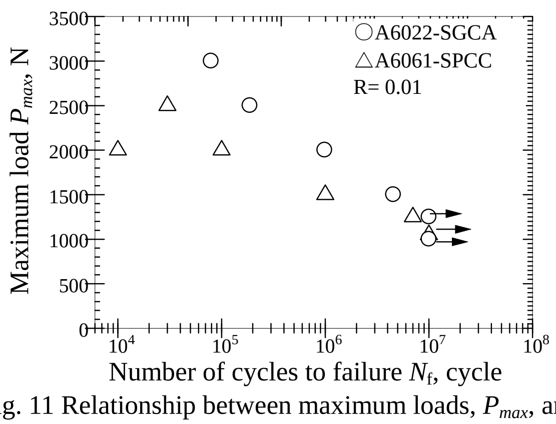


Fig. 11 Relationship between maximum loads, P_{max}, and number of cycles to failure, N_f.

Typical macroscopic appearances of fatigue fracture surface of dissimilar welds are shown in Fig. 12. The fatigue fracture occurred along the interface between the upper and lower sheets. This failure mode is similar to that under static loading condition as in Fig. 9

However, a detail observation on the fatigue fracture surface using EDS analysis shows that Al adhesive were not observed on almost of the joint fracture surface. This indicates that fatigue crack grows between the lower steel sheet and interface layer, as show in Fig 13. In the meantime, zinc was not found at the weld zone but only at the periphery of the fracture surface as shown in Fig. 12 (b) and Fig. 12 (c).

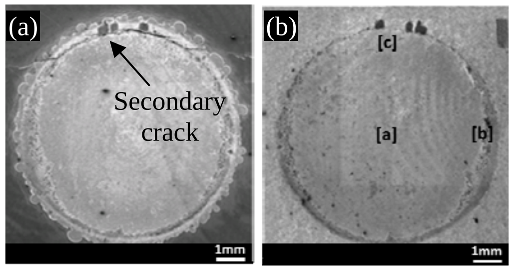


Fig. 12 SEM macrographs of tensile fracture surface of dissimilar weld: P_{max}= 2000N, N_f = 1.0x10^6 cycle, (a) al side (b) steel side.

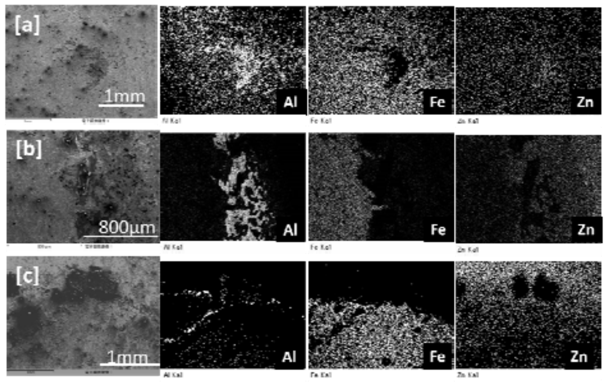


Fig. 13 EDS analysis of the fatigue fracture surface: (a) Center, (b) edge, and (c) secondary crack of joint in Fig. 12, respectively.

It should be noted that final fracture are occurred along the interface at all loading condition, while a secondary crack grew into the upper sheet as shown in Fig.12. The secondary crack was observed in all specimens. The SEM images of secondary crack fracture surface are shows in Fig. 14 and magnified view of the crack initiation site are shows in Fig. 14(a), Fig. 14(b) and Fig. (c). The crack was initiated at the interface then grew into the al sheet.

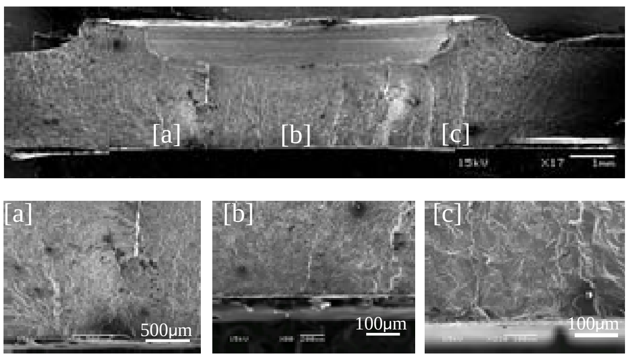


Fig. 14 SEM micrograph of the secondary crack fracture surface: P_{max}= 2000N, N_f = 1.0x10^6 cycles: Magnified view at region [a], region [b] and region [c].

Figure 15 is a sample of cross-section Al side weld zone that parallel to the loading direction shows that the secondary crack occurred in TMAZ region, as the region where the lower Vickers hardness is measured and not the zinc layer that flow towards Al sheet.

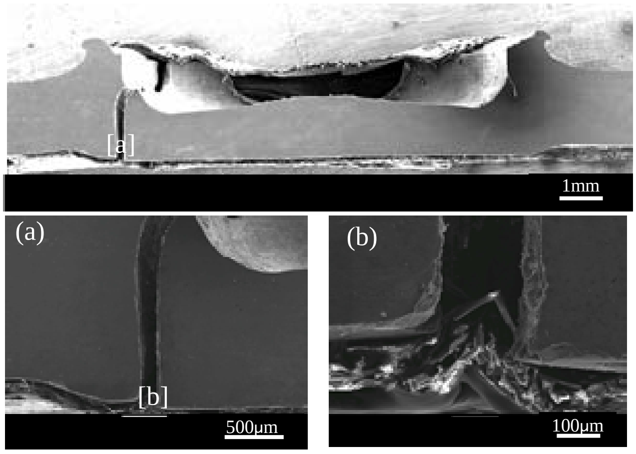


Fig. 15 SEM micrograph of the secondary crack fracture surface: P_{max}= 2500N, N_f = 6.0x10^5 cycles: Magnified view at region (a) and region (b).

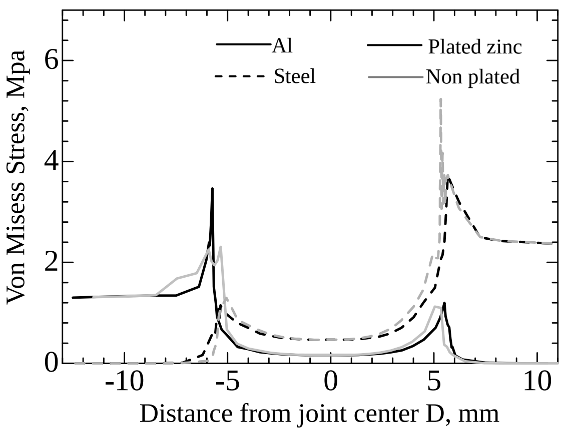


Fig. 16 Von Misses stress of both sheet at the interface.

FEM analysis was conducted regarding the solidified plated zinc layer at the weld periphery. Fig. 16 showed the Von Misses stress results of both sheet with and without the solidified plated zinc layer condition. The maximum Von Misses stress for non-plated steel sheet higher than the plated zinc layer steel. Also, the solidified plated zinc layer gives a larger bonded area and lowering the stress distribution in the lap joint during the fatigue testing. As indicates in Fig. 12 and Fig. 13, it is possibly that the interface fatigue crack initiated between the IMC and steel surface at the steel side.

In the present welding condition a joint of FSSW joint has been obtained successfully. The fatigue strength of Al-SGCA dissimilar weld is higher than Al-SPCC especially at higher fatigue loading condition. The substantially improved of fatigue resistance AL-SGCA was the result to the stress relaxation surrounding the weld nugget.

4. CONCLUSIONS

This study investigated the dissimilar lap welds between galvanized steel and aluminum alloy sheets. It aimed at characterizing the intermetallic compounds (IMC) formed during spot welding and the plated zinc layer behavior in the FSSW joint.

(1) EDS analysis results indicate that the intermetallic compound (IMC) layer was formed at the Al/Fe interface during FSSW.

(2) The fatigue crack grows between the lower steel sheet and interface layer and grew through the interface layer and steel sheet.

(3) The fatigue strength of Al-SGCA dissimilar weld is higher than Al-SPCC especially at higher fatigue loading condition. The substantially improved of fatigue resistance AL-SGCA was the result to the stress relaxation surrounding the weld nugget.

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