A6061/SS400 異種金属摩擦攪拌接合継手の疲労挙動*

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Fatigue behavior of dissimilar A6061/rolled steel (SS400) friction stir welds*

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The dissimilar welds between aluminum (Al) alloy, A6061-T6, and rolled steel, SS400, had been fabricated by a friction stir welding (FSW) technique. The FSW tool was offset to the Al side and the probe was inserted only into Al plate. Based on the microstructural observation, small steel fragments were recognized in Al side due to the scratching of steel side surface by the probe. Subsequently, hardness, tensile and fatigue tests of Al similar and Al/steel dissimilar welds had been conducted. The hardness of stir zone (SZ) in Al side was lower than the base metal due to the dissolution of hardening precipitates during welding, where the lowest hardness located near the interface and thermo-mechanically affected zone (TMAZ) in Al side. The tensile strength of the dissimilar weld was lower than that of the similar one. Static fracture of the dissimilar weld occurred through the interface, where the hardness was the lowest, while through the TMAZ in the similar weld. The dissimilar welds exhibited lower fatigue strengths than the similar ones. The fractographic analysis revealed that fatigue crack initiated at the interface between Al and steel, but propagated through Al alloy near the interface. Based on the fracture mechanics, it was concluded that the lower fatigue strengths of the dissimilar welds could be attributed to the lower fatigue crack initiation resistance.

Key Words: Friction stir welding; Dissimilar weld; Fatigue behavior; Aluminum alloy; Steel

1. Introduction

In the automobile industry, Al alloys are increasingly used to reduce the weight of car components and to achieve high fuel efficiency. However, steel is still widely applied because of the higher strength level and lower costs of steel than Al alloys. Thus it is important to fabricate dissimilar welds between Al alloy and steel to construct Al-steel hybrid components. Butt fusion welding between Al and steel generally leads to low joint efficiency due to the formation of thick intermetallic compound along the interface. Recently, FSW is drawing attention for the fabrication of dissimilar welds because FSW is a solid state joining process, and the formation of intermetallic compounds could be suppressed. There have been several researches concerning with the joining between Al and steel by FSW process¹⁻⁸⁾, and revealed relatively high joint efficiency of Al/steel dissimilar welds. Fukumoto et al. had reported that the tensile strength of Al/steel weld was dependent on the offset distance of the tool from the weld center²⁾, and Yasui et al. had revealed that the joining between Al and steel was achieved by the formation of

very thin intermetallic layer along the interface⁶⁾. There have been some researches about static strengths and microstructures of Al/steel dissimilar welds. However, to achieve the high reliability of actual components, it is very important to understand the fatigue behavior of dissimilar welds, while the investigation about fatigue performances was very limited.

In the present study, the dissimilar welds between Al alloy, A6061-T6, and rolled steel, SS400, were fabricated by an FSW technique, and the fully reversed axial fatigue tests were conducted. The fatigue strength and fracture mechanism were investigated in comparison with A6061-T6 similar welds.

2. Experimental details

2.1 Materials

The material used is A6061-T6 Al alloy plate with the length of 100mm, the width of 77mm and the thickness of 5mm. The counter material is rolled steel plate classified as SS400 by Japanese industrial standard, JIS G3101, with the same length and width, but the thickness is 4.2mm. The microstructures of the materials are shown in Fig. 1. SS400 has equiaxed grains, while the grains of A6061-T6 plate are elongated by the rolling process. The chemical composition of A6061-T6 is Si: 0.67, Fe:0.4, Cu: 0.28, Mn: 0.08, Mg: 1.0, Cr: 0.18, Zn: 0.02, Ti: 0.01 and Al: Bal. (wt%). The mechanical properties of materials are summarized in Table 1. The chemical composition of SS400 is P: <0.05, S: <0.05, and mechanical properties are in Table 1, according to JIS G3101.

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Fig. 1 Microstructures of base metal: (a) 6061-T6, (b) Rolled steel (SS400).

Table 1 Mechanical properties of materials.

Material	0.2% proof stress $\sigma_{0.2}$ (MPa)	Tensile strength σ_b (MPa)	Elongation δ (%)	Vickers hardness HV
A6061-T6	290	322	13	101
SS400	<245	400~510	<21	91

*The mechanical properties of SS400 are based on JIS G 3101. Vickers hardness of SS400 was measured by a micro-Vickers hardness tester.

2.2 Welding conditions

The Al and steel plates were butt welded along the longitudinal direction by means of a milling machine (MAKINO KE-55) with a FSW tool. The tool has the flat shoulder surface with the diameter of 14mm and the M6-threaded probe with the length of 4.6mm. The steel plate was settled on the advancing side (A-side) where the tool traveling direction corresponded to the rotational direction. And the Al plate was settled on the other side, namely the retreating side (R-side)⁵⁾. The tool probe was inserted into Al plate with the offset of 0mm from the interface as schematically shown in Fig. 2. The Al plate is slightly thicker than the steel one. Consequently the tool shoulder surface was plunged only into the Al plate, and the tool shoulder surface and the side of the probe were just touching on the surface and side-surface of steel plate, respectively. Prior to the welding, the edge of the steel plate was finished by a surface grinder to achieve a flat surface, while Al plate was welded in the as-received condition. Al/Al similar welds were also fabricated using the same tool for comparison. The welding conditions for the similar and dissimilar welds are summarized in Table 2. The welding conditions were settled based on the pre-tensile tests to achieve high static strengths. Both tool rotational and traveling speeds are much lower in the joining condition between Al and steel dissimilar metals. It should be noted that the welding conditions could be strongly dependent on the tool geometry and welding equipment. Thus, the optimal welding conditions in Table 2 are for the tool geometry described above and for the milling machine, MAKINO KE-55.

Fig. 2 Schematic illustration of welding parameter.

Table 2 Welding conditions.

	Al/Al joint	Al/Fe joint
Tool shoulder diameter (mm)	$\phi 14$	
Tool probe diameter (mm)	$\phi 6$	
Tool probe length (mm)	4.6	
Rotating speed (rpm)	1200	800
Travelling speed (mm/min)	200	50
Tool offset (mm)	-	0
Tool plunge depth (mm)	0	0.05
Tilt angle (deg.)		0

Fig. 3 Fatigue specimen configuration.

2.3 Specimens and procedures

Micro-Vickers hardness tests were conducted at the load of 4.9N. The tensile tests were performed using a universal tester with the stress increasing ratio of about 10N/mm²/s. The tensile specimen has 12.5mm in the width and 50mm in the gauge length, which is classified as 13B-type tensile specimen according to JIS Z 2201. Both upper and lower surfaces are milled off in the depth of 0.6mm to remove the effect of welding defects, thus the thickness of the gauge section is 3mm. Fully reversed fatigue tests were conducted by an electro-hydraulic testing machine using sinusoidal waveform with the test frequency of 10Hz. The testing environment is ambient air. The fatigue specimen configuration is shown in Fig. 3. The thickness of the gauge section is 3mm because the upper and lower surfaces were removed. Specimen surface was mirror finished prior to the

Fig. 4 Microstructures of Al/Al similar weld: (a) Macroscopic view, (b) SZ, (c) TMAZ.

Fig. 5 Microstructures of Al/steel dissimilar weld: (a) Macroscopic view, (b) Interface, (c) SZ, (d) TMAZ, (e) HAZ.

fatigue tests.

3. Results

3.1 Microstructures

Figure 4 shows the microstructures of Al/Al similar welds. The grains in the stir zone (SZ) are refined due to dynamic recrystallization during welding and severe plastic deformation is recognized in the thermo-mechanically affected zone (TMAZ). The microstructures of Al/steel dissimilar weld are revealed in Fig. 5. The probe of FSW tool was offset to the Al side, thus the

Fig. 6 Hardness profiles at the center of specimen thickness.

Fig. 7 Hardness profiles of dissimilar weld at the center of specimen thickness and 0.5mm from top and bottom surfaces.

probe was not inserted into the steel. However, the interface of steel (Fig. 5 (b)) is not flat. The rough interface morphology indicates that the probe surface slightly touched the steel, resulting in the scratching of side surface. Consequently, small fragments of steel were recognized in the Al-side SZ as shown by the arrow in Fig. 5 (c). It is noteworthy that the distribution of steel fragments corresponds to the dark area of the SZ in the macroscopic view (Fig. 5 (a)).

3.2 Hardness profile

The hardness profiles of the similar and dissimilar welds were measured along the mid-thickness on the side surfaces. The profiles are revealed in Fig. 6. In the similar weld, a typical hardness profile in the friction stir welds of T6-treated 6000 series Al alloy is recognized where the hardness in SZ is lower than that of base metal (BM) due to the dissolution of hardening

Table 3 Tensile strengths of welds.

Joint	Tensile strength σ_B (MPa)	Elongation δ (%)
Al/Al	240	4
Al/Steel	192	2

Fig. 8 Steel-side tensile fracture surfaces in Al/steel weld: (a) Macroscopic view, (b) Magnified view of area "A" in (a), (c) Magnified view of area "B" in (a).

precipitates, and the bottoms of hardness profile locate at the TMAZ⁹⁾. In the dissimilar weld, the weld center of the figure was defined as the interface between Al and steel plates. The hardness is lower in the SZ than in the BM and the bottom is recognized at the TMAZ in the Al side similar to Al/Al weld. It should be noted that the other bottom of hardness in Al/steel dissimilar weld locates near the interface. The highest peak of hardness in steel side near the boundary was due to work hardening induced by the scratching of side surface by the probe. The hardness of SZ was lower in the dissimilar weld than in the similar weld. The traveling speed of the tool was much slower in the joining condition of dissimilar weld (see Table 2), and consequently resulted in the higher heat input and lower hardness in the SZ. The hardness profiles of dissimilar weld at the mid-thickness and 0.5mm from the top and bottom surfaces are shown in Fig. 7. It reveals that the bottoms of hardness locate near the interface and TMAZ through the thickness.

3.3 Tensile tests

The tensile strength, σ_B , of BM is 315MPa, while those of Al/Al similar and Al/steel dissimilar welds were 240MPa and 192MPa, respectively as shown in Table 3. The tensile fracture occurred through the TMAZ in the similar weld, and thus the lower σ_B of the weld than the BM could be attributed to the lowest hardness distribution along the TMAZ (see Fig. 6). The tensile fracture surface was fully covered by dimples. In the dissimilar weld, the tensile fracture occurred along the interface

Fig. 9 S-N diagram.

Fig. 10 Side view of fatigue-fractured Al/Al similar weld ($\sigma_a=130$ MPa, $N_f=2.1 \times 10^6$).

between Al and steel. Steel-side tensile fracture surfaces are shown in Fig. 8. As shown in the magnified view of area "A" (Fig. 8 (b)), the fracture surface is covered by dimples, indicating high bonding strength between Al and steel. Figure 8 (c) is the magnified view of area "B", and the dotted area reveals that the flat steel surface is exposed in some areas of fracture surface. The flat steel surface indicates that the interface bonding strength is not high enough to lead the static failure in Al side resulting in dimple-covered fracture surface. It is considered that the interfaces with relatively weak bonding strength are locally distributed as shown by the dotted area in Fig. 8, and could have detrimental effect on the tensile strength of the dissimilar welds. In this case, the tensile strength of dissimilar weld was rather lower than BM. However, it is still important to investigate the fatigue behavior in the dissimilar weld in the engineering point of view because the dissimilar weld has the interface between Al and steel, where stress singularity could occur due to the different elastic moduli.

3.4 Fatigue tests

Figure 9 shows the S-N diagram of Al/Al similar and Al/steel dissimilar welds. The fatigue limits are 120MPa and 80MPa for the similar and dissimilar welds, respectively. The number of fatigue-fractured samples is relatively small. But the fatigue

Fig. 11 Fatigue fracture surfaces of Al/Al similar weld: (a) Macroscopic view (dotted area represents the crack initiation site), (b) Crack initiation site, (c) Magnified view of (b). ($\sigma_a=130\text{MPa}$, $N_f=2.1 \times 10^6$)

Fig. 12 Side view of fatigue-fractured Al/steel dissimilar weld ($\sigma_a=140\text{MPa}$, $N_f=1.3 \times 10^5$).

limits are still valid because the stress step in the fatigue tests near the fatigue limit level was set to be small value of 10MPa. The dissimilar welds exhibited lower fatigue strengths than the similar ones. In the similar welds, fatigue failure occurred through the TMAZ as shown in Fig. 10, indicating that the fracture path was correspondent with that under static loading. The fatigue fracture surfaces near the crack initiation site in the similar weld are indicated in Fig. 11. No welding defect was found at the crack initiation site, revealing that the fatigue crack initiated due to the localized cyclic slip deformation at the softening site, namely at the TMAZ.

In the dissimilar welds, fatigue crack initiated and propagated through the interface between Al and steel as shown by the macroscopic view of the fatigue-fractured weld (Fig. 12). Figure 13 reveals the typical fatigue fracture surfaces of dissimilar welds observed on the steel side. Fig. 13 (a) is the macroscopic view, and Fig. 13 (b) is the backscattered electron image (BEI) of Fig. 13 (a). In the BEI, dark and bright areas correspond to Al and steel, respectively. The steel-side fracture surface is nearly fully covered by Al, indicating that the fatigue crack grew through Al alloy very close to the interface (see Fig. 12). The dotted areas in Fig. 13 (a) and (b) represent the fatigue crack initiation site, and Fig. 13 (c) shows the magnified view of the initiation site. Fig. 13 (d) is the BEI of Fig. 13 (c). The flat surface is recognized at the

Fig. 13 Fatigue fracture surfaces of Al/steel dissimilar weld observed on the steel side: (a) Macroscopic view (dotted area represents the crack initiation site), (b) BEI of (a), (c) Crack initiation site, (d) BEI of (c). ($\sigma_a=100\text{MPa}$, $N_f=3.5 \times 10^5$).

Table 4 Decreasing ratios of tensile strength and hardness.

Joint	Tensile strength σ_B (MPa)	Joint efficiency (%)	Minimum Vickers hardness HV_{min}	Vickers hardness efficiency* (%)
Al BM	322	100	101	100
Al/Al	240	74.5	63	62.4
Al/steel	191	59.3	53	52.5

*Vickers hardness efficiency was defined as the minimum hardness of joint normalized by the average hardness of base metal.

crack initiation site (Fig. 13 (c)), and the BEI (Fig. 13 (d)) reveals that steel is exposed at the initiation site. Consequently, it could be concluded that fatigue crack initiated at the boundary between Al and steel and then propagated into Al alloy very close to the boundary.

4. Discussion

4.1 Tensile strength

Table 4 summarizes the joint and hardness efficiencies in Al/Al similar and Al/steel dissimilar welds. Join efficiency was generally defined as the tensile strength of joint normalized by that of the base metal (BM). Thus the joint efficiency of Al/steel dissimilar weld was defined as the tensile strength of dissimilar weld, $\sigma_{B \text{ Al/steel}}$, divided by that of Al BM, $\sigma_{B \text{ Al-BM}}$. In addition, the minimum Vickers hardness of joint was normalized by the average hardness of BM and defined as hardness efficiency. The hardness efficiencies in the similar and dissimilar welds are 62.4% and 52.5%, respectively. The larger drop of hardness in the

Fig. 14 S-N diagram in terms of normalized stress amplitude.

Fig. 15 Fatigue crack initiated on the specimen surface ($\sigma_a=140\text{MPa}$, $N=2.7 \times 10^5=0.5N_f$)

dissimilar weld could be attributed to the higher heat input depending on the welding conditions, especially on the slower tool traveling speed (Table 2). The joint efficiency of the similar weld was 74.5%, while that of the dissimilar weld was 52.5%. The static fracture occurred through the zone in which the hardness was the lowest, so that the lower hardness could be related to the lower tensile strength in the dissimilar weld. But there should be the other reason for the lower tensile strength in the dissimilar weld because the difference of joint efficiency between similar and dissimilar welds was larger than that of hardness efficiency. On the tensile fracture surface of the dissimilar weld, flat steel face without Al dimples was partly exposed as shown in Fig. 8 (c). It is considered that the low bonding strength areas were locally distributed along the interface and also responsible for the lower tensile strength in the dissimilar weld.

4.2 Fatigue strength

In the friction stir welds of 6000 series Al alloys, dynamic aging occurs in the SZ and TMAZ during cyclic loading, resulting

Fig. 16 Fracture surfaces of Al/steel dissimilar weld statically fractured after fatigue test: (a) Macroscopic view (dotted line represents the fatigue crack front), (b) Magnified view of area "A" in (a), (c) Magnified view of (b), (d) Magnified view of area "B" in (a), (e) Magnified view of (d). ($\sigma_a=100\text{MPa}$, $N=1.7 \times 10^5=0.5N_f$).

in the different hardness profiles before and after fatigue tests⁹⁾. Therefore, the hardness profiles were measured after the fatigue tests and plotted in Fig. 6. The hardness profiles before and after fatigue tests are nearly the same in both similar and dissimilar welds. It could be concluded that dynamic aging did not occur in this case and had no effect on the fatigue strength.

Stress amplitudes, σ_a , in the S-N diagram (Fig. 9) were normalized by the tensile strengths, σ_B , of each weld and the normalized S-N curves are indicated in Fig. 14. The dissimilar weld exhibits lower fatigue limit than the similar one, even if the stress amplitude was normalized by the tensile strength. It implies that cyclic loading has more detrimental effect on the fatigue limit of dissimilar welds than static loading.

The total fatigue life of welds consists of the fatigue crack initiation life, N_i , and fatigue crack propagation life, N_p . In terms of crack propagation life, it is important to understand the relationship between crack growth rates and stress intensity factor K . Ishida et al. had analyzed the stress intensity factor of the crack along the interface between two materials with different elastic moduli¹⁰⁾. Based on their conclusion and the elastic moduli of Al and steel, the interface crack between Al and steel has lower stress intensity factor than the crack in homogeneous Al matrix when the same load is applied to the crack with the same length. Thus,

it is considered that the fatigue crack in Al/Al similar weld could grow faster than the crack near the interface between Al and steel in Al/steel dissimilar weld at the same stress level. However fatigue lives of the dissimilar welds were shorter than those of the similar ones as shown in Fig. 9 and 14. Consequently, fatigue crack initiation life might be the controlling factor of the shorter fatigue life of dissimilar welds.

Subsequently, fatigue crack initiation mechanism was investigated in detail by a plastic replication technique and fractographic analysis. Figure 15 shows the typical fatigue crack observed in Al/Al similar weld when the number of cycles was about 50% of total fatigue life, namely the cycle ratio, $N/N_f \approx 0.5$. The length of small crack was about $50\mu\text{m}$, and it was found that the small crack grew along the TMAZ showing frequent coalescence with other small cracks until final fracture. In Al/steel dissimilar weld, the crack initiation could not be followed by a plastic replication technique because it was very difficult to distinguish small fatigue crack from the boundary line between Al and steel. Hence, the fatigue test of Al/steel dissimilar weld was terminated at the cycle ratio, N/N_f , of 0.5 based on the S - N diagram, and the specimen was statically loaded until final fracture to separate static and fatigue fracture surfaces based on the fractographic analysis. Figure 16 shows the steel-side fracture surfaces. As shown by the magnified views of the location "B" in Fig. 16 (a), many dimples are recognized revealing static fracture mode (Fig. 16 (d), (e)). However, in the right low corner end, rather flat fracture surface with Al is seen, which is typical for the fatigue crack growth mode (Fig. 16 (b), (c)). The boundary between dimple-covered area and flat area is shown by the white dotted line in Fig. 16 (a), representing the fatigue crack front. The surface crack length was larger than 1mm at a half of the total fatigue life, while the crack length was just $50\mu\text{m}$ in the similar weld (Fig. 15). In this case, stress levels are different between Figs. 15 and 16, but the stress was arranged to be the fatigue life would be around 1×10^5 cycles. Consequently, it could be concluded that the lower fatigue life of dissimilar welds was attributed to the lower crack initiation resistance. It shall be considered that the singularity at the interface between Al and steel had detrimental effect on the fatigue crack initiation behavior.

5. Conclusions

The butt welds between Al alloy (A6061-T6) and rolled steel (SS400) plates had been fabricated by an FSW technique. The tensile and fatigue strengths and failure modes were discussed in comparison with Al/Al similar welds. The results are summarized as follows.

1. Both Al/Al similar and Al/steel dissimilar welds had lower

hardness and tensile strength than the base metal (BM) due to the dissolution of hardening precipitates during welding.

2. The tensile strength of Al/steel dissimilar weld was lower than that of Al/Al similar one. The lower hardness in the weld zone of dissimilar weld due to higher heat input and the local weak bonding between Al and steel led to the lower tensile strength.
3. Al/steel dissimilar welds exhibited lower fatigue strengths than Al/Al similar ones, even if the stress amplitudes were normalized by their tensile strengths, indicating that cyclic loading had more detrimental effect on Al/steel dissimilar weld than static loading.
4. Based on the fracture mechanics and fractographic analyses, it was concluded that the lower fatigue crack initiation resistance along the interface of Al/steel dissimilar welds led to the lower fatigue strengths.

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