

Fatigue Properties of Butt Welded Aluminum Alloy and Carbon Steel Joints by Friction Stirring

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Abstract. The butt dissimilar joints of Al-Mg-Si alloy JIS A6063 and carbon steel JIS S45C by means of friction stir welding were prepared for investigating fatigue properties of the joints. The joining tool used has cemented carbide thread probe and a shoulder made of alloy tool steel. All the fatigue tests were carried out under a load-controlled condition with a load ratio $R=0.1$ in air at room temperature. From the experimental results, it was found that hardness near the interface in A6063 was lower than that of base material. Three types of fatigue fracture occurred even in case of same welding condition. The first one was fracture at boundary between the lower hardness region and base material in A6063, the second type was initiated in the stir zone by FSW process and the last one was fracture at interface. Fatigue strength in case of the second one was lower than others. Furthermore, to investigate the effect of heat treatment on fatigue properties of the dissimilar joints, fatigue tests were also carried out with using the specimens which were heat treated under the same condition to aging process in T6 treatment. Fatigue fracture was initiated at interface between A6063 and S45C in case of the heat treated specimen, but fatigue strength was improved approximately 25% as compared with that of the non-heat treated specimen.

1. Introduction

It is a common knowledge that for reducing weight of mechanical structures, using lightweight metal such as aluminum alloy or magnesium alloy instead of steel is very much effective. However, since lightweight metal has generally lower strength as compared with steel, constructing all structures with lightweight metal is hardly possible. Friction stir welding (FSW) is one of the latest joining techniques which can weld the materials in state of solid phase. Therefore, it is expected for joining of dissimilar materials. The authors have previously reported characteristics and mechanical properties of Al alloy and steel joint by FSW ^{[1]-[5]} or fundamental fatigue properties of friction stir spot welding ^{[6]-[8]}.

It is important to clarify the mechanical properties especially fatigue properties of the dissimilar joint before it will be used in the actual components and structures, however there are few reports regarding fatigue properties of the joints. In this study, the butt dissimilar joints of Al-Mg-Si alloy JIS A6063 and carbon steel JIS S45C by means of friction stir welding were prepared for



investigating the basic fatigue properties of the joints. On the other hand, there are some reports regarding the aging effect for improving mechanical properties on friction stir welds of precipitation hardening aluminum alloy [9]-[11]. However, there are very few reports about the effect of aging on the dissimilar joints. In this study, effect of heat treatment on fatigue properties of the A6063/S45C dissimilar joint was also investigated.

2. Experimental procedures

2.1. Materials and FSW conditions

In this study, carbon steel JIS S45C and Al-Mg-Si alloy JIS A6063-T5 which were both 60 mm in width, 300 mm in length and 6 mm in thickness, were used for the butt dissimilar joints by means of friction stir welding (FSW). The chemical compositions and basic mechanical properties of both materials are summarized in Table 1 and Table 2, respectively. The welding tool used in this study has cemented carbide M5 thread probe and a shoulder made of alloy tool steel with a diameter of 20 mm. Figure 1 shows schematic illustration of FSW. The probe was plunged into A6063 and moved along the weld line. The offset displacement which means deviation value between weld interface of A6063 and S45C and side surface of the tool was 0.05 mm in S45C as illustrated in Fig. 1. The rotating direction and welding direction were identical in S45C side, i.e. the advancing side (AS) was S45C and retreating side (RS) was A6063 as also illustrated in Fig. 1. Rotating speed of the tool was 2000 rpm and welding speed was 500 mm/min in this study.

2.2. Heat treatment of the dissimilar joints

In this study, some butt welded joints by FSW were heat treated. The heat treatment condition was as follows, the joints were heated for eight hours by using air furnace under the condition of 523 K (250 °C), after that the joints were air cooled. This condition was in compliance with the aging process of T6 treatment for A6063. After the aging process, fatigue specimens were machined from the joints as described later in detail.

2.3. Hardness distribution

To clarify hardness distribution around the welding interface, Vickers hardness test was carried out on the cross section of the joint. Testing load were 300 gf for A6063 and 1000 gf for S45C

Table1 Chemical compositions of the materials used. (mass %)

	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al	C	P	S	Ni
A6063-T5	0.43	0.17	0.00	0.03	0.48	0.00	0.00	0.01	Re	-	-	-	-
S45C	0.18	Re	0.12	0.64	-	0.07	-	-	-	0.46	0.14	0.03	0.06

Table2 Mechanical properties of the materials used.

	Tensile strength σ_b , MPa	0.2%Proof stress, MPa	Yield stress, MPa	Young's Modulus, GPa
A6063-T5	205	145	-	68.6
S45C	605	-	345	205

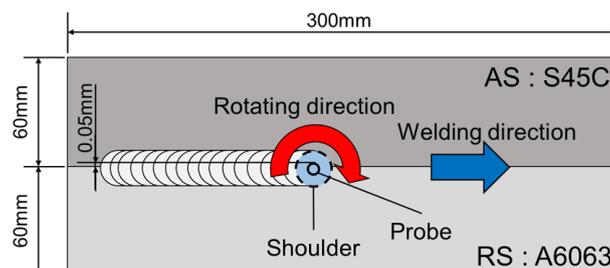


Fig. 1 Schematic illustration of FSW.

respectively, and holding time was 10 seconds. The relationship between distance from the interface and Vickers hardness is shown in Fig. 2. Data plots located in right side of the interface indicate the hardness of A6063, and data plots in left side indicate the hardness of S45C. It can be seen from the figure that there is lower hardness region near the interface in case of non-heat treated A6063 specimen (\circ). The average hardness of this region where distance from the interface is less than approximately 9mm was 62 Hv, which was significantly lower than that of A6062 base metal (77 Hv). This region seems to be the stir zone (SZ) and the thermo-mechanically affected zone (TMAZ) by FSW process [9]. On the other hand, in case of heat treated specimen (\blacktriangle), the average hardness of this region recovered to approximately 89 Hv. And the hardness distribution in the region where distance from the interface is larger than 10mm, was almost similar to that in case of non-heat treated specimen. This characteristic is similar to the aging effect of friction stir welds between the precipitation hardening aluminum alloys [9]-[11], it had been clarified that in case of the dissimilar joints same phenomenon occurs.

2.4. Specimen and tests conditions

In this study two kinds of fatigue specimen were used. The shapes and dimensions of the fatigue specimens are shown in Fig. 3, respectively. Type-A specimen where the welding interface aligned with the center of specimen was used for both tensile and fatigue tests, and Type-B specimen where the distance between welding interface and specimen center was 5 mm, was used for fatigue tests. The gauge parts of both specimens were polished with emery paper up to grade of #2000 longitudinally and final polishing was conducted by using diamond paste with grain size of 10 μm .

Tensile tests were carried out by using universal testing machine with crosshead speed of 0.5 mm/min. A fatigue test machine with 19.6 kN capacities was used for fatigue tests. All the fatigue tests were carried out under a load-controlled sinusoidal wave form condition with a stress ratio $R=0.1$ and frequency $f=20\text{Hz}$ in air at room temperature. After the fatigue tests, fracture surfaces were observed in detail by using a scanning electron microscope (SEM).

3. Results and discussions

3.1. Tensile tests

From the results of tensile tests, it was found that the average tensile strength σ_B in case of non-heat treated specimen was approximately 140 MPa. On the other hand, in case of heat treated specimen, the average tensile strength σ_B was approximately 195 MPa which was about 40% improvement compared with that of the non-heat treated specimen. In both cases, tensile fracture

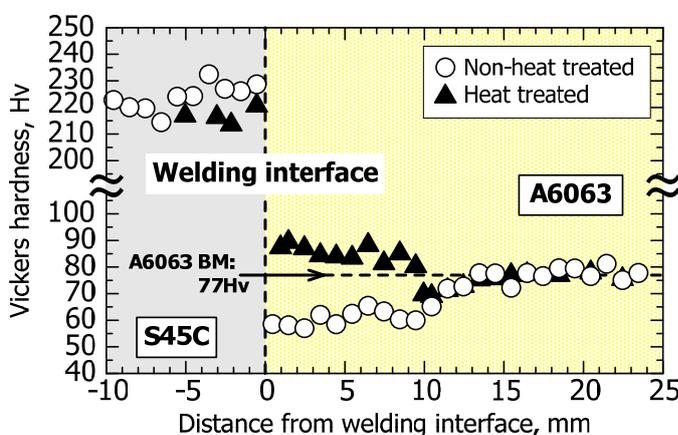


Fig. 2 Hardness distribution around the interface.

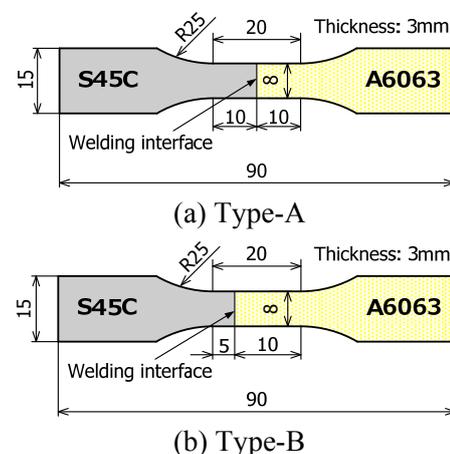


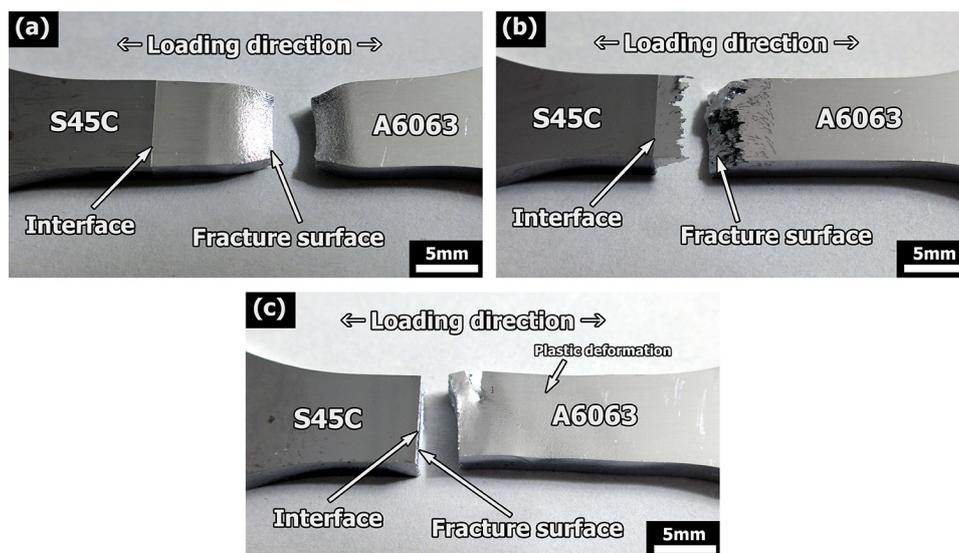
Fig. 3 Shapes and dimensions of the specimen used.

occurred at the site where distance from the interface is approximately 10mm in A6063. This site almost correspond to a location of boundary between the lower hardness region in case of non-heat treated specimen or recovered hardness region in case of heat treated specimen, and base metal respectively, as described in Fig. 2.

3.2. Fatigue fracture modes

In this study, three types of fatigue fracture modes occurred in case of non-heat treated specimen. Overviews of the fractured specimens are shown in Fig. 4. Figure 4(a) is a typical observation of the specimen fractured at a boundary between the lower hardness region and base metal in A6063. It is clearly found that significant plastic deformation occurred around the fracture surface. Figure 4(b) shows the specimen fractured at around the location where distance from the interface is approximately 2-3 mm in A6063. This location seems to be a center of the tool path in FSW process, i.e. a center of the stir zone (SZ). Figure 4(c) shows the specimen fractured at interface, and significant plastic deformation was observed clearly where the fatigue fracture occurred in the case of Fig. 4(a).

On the other hand, in the case of heat treated specimen, fatigue fracture occurred at welding interface in all specimens. Figure 5 is a typical observation of the fractured specimen. It is found that there are other cracks near fracture surface. Since striation was observed on the crack surface, this



(a) σ_a : 55MPa, N_f : 1.64×10^5 , (b) σ_a : 40MPa, N_f : 3.41×10^4 , (c) σ_a : 50MPa, N_f : 2.02×10^5

Fig. 4 Overviews of fatigue fractured non-heat treated specimens.

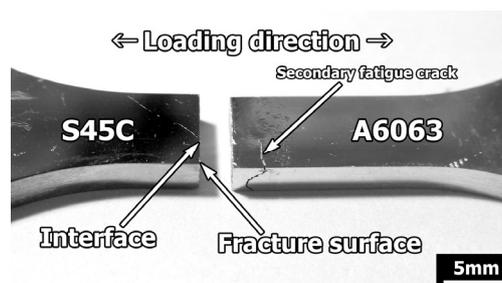


Fig. 5 Overview of fatigue fractured heat treated specimen.

(σ_a : 60MPa, N_f : 4.06×10^4)

kind of crack seems to be a secondary fatigue crack, as described later in detail. And no significant plastic deformation was observed where the fatigue fracture occurred in the case of Fig. 4(a).

3.3. S-N curves

The relationship between applied stress amplitude and number of cycles to failure (S-N curve) is shown in Fig. 6. In the figure, data points with arrow show that no failure occurred up to the testing cycles of 1×10^7 . Circle plots indicate the results of non-heat treated specimen and triangle plots indicate the results of heat treated specimen. The difference in painting on data plots indicates the difference of fatigue fracture mode. Further, data points with * or ** show the results of using Type-A specimen, and the other plots show results of using Type-B specimen, as described later in detail.

It can be seen from the figure that for non-heat treated specimen, fatigue strength in case of fracture in stir zone (\circ) was lowest and fatigue strength in case of fracture at boundary between the lower hardness region (TMAZ) and base metal (BM) in A6063 (\bullet) was highest, although there is a large dispersion. The fatigue strength at 1×10^7 cycles was approximately 40 MPa (maximum stress: 89 MPa). On the other hand, for heat treated specimen, fatigue strength was higher than those of non-heat treated specimen. The fatigue strength at 1×10^7 cycles was around 50 MPa (maximum stress: 111 MPa) which was about 25% improvement compared with that of non-heat treated specimen.

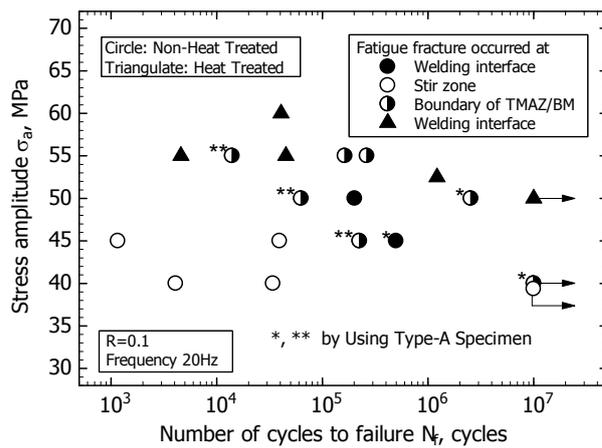


Fig. 6 S-N curves.

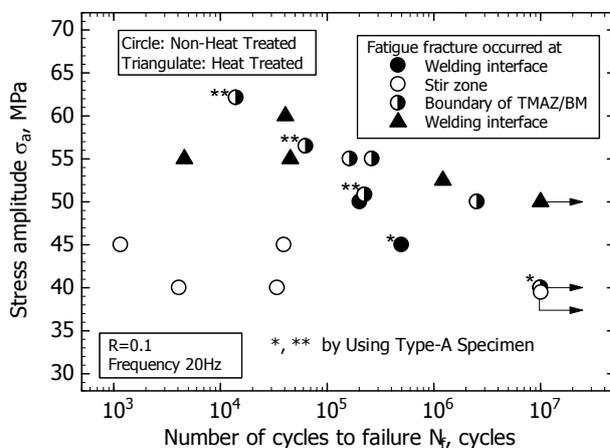


Fig. 7 Revised S-N curves.

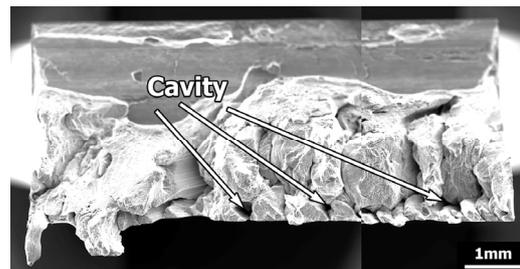


Fig. 8 Fracture surface of the non-heat treated specimen (σ_a : 40MPa, N_f : 3.41×10^4).

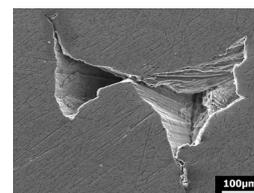


Fig. 9 Cavities (defects) in stir zone.

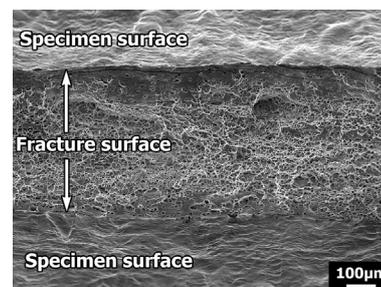


Fig. 10 Fracture surface of the non-heat treated specimen (σ_a : 55MPa, N_f : 1.64×10^5).

According to the data base of The Japan Aluminium Association ^[12], fatigue strength of A6063-T5 at 1×10^7 cycles under the condition of stress ratio $R=-1$ is 70 MPa. By using the modified Goodman's line, fatigue strength of A6063-T5 under the condition of $R=0.1$ had been estimated approximately 49.4 MPa in stress amplitude, which is almost similar level to that of the heat treated specimen. Therefore, the joint efficiency in fatigue strength of the heat treated dissimilar joint used in this study is thought to be almost 100 %.

3.4. Considering the shape effect of fatigue specimen

In Fig. 6, data points with * or ** show the results of using Type-A specimen that the welding interface and center of specimen were aligned. Furthermore, the plots with ** indicate that fracture occurred at boundary between the lower hardness region and base metal, that was approximately 10 mm from the interface in A6063. In this region, the stress seemed to concentrate by influencing of the fillet part ($R=25$) in Type-A specimen. The stress concentration factor α is 1.129 for this shape ^[13]. Therefore, although it is simplified method, applied stress in these cases must be correct conveniently by multiplying α . The revised S-N curve is shown in Fig. 7. From the figure, it is clarified that the dispersion in fatigue lives become smaller in case of the specimen fractured at boundary between TMAZ and BM.

3.5. Observation of the fracture surface and specimen surface

SEM micrograph of the fracture surface on the non-heat treated specimen which fractured in stir zone is shown in Fig. 8. There are many large grains which are millimeter size and a lot of cavities are also found. Cross sectional observation of stir zone in the non-heat treated specimen unused is shown in Fig. 9. Some cavities (defects) which are similar to the cavities observed on the fracture surface are found, and these cavities were thought to generate during FSW process. Since fatigue strength of the specimens which fractured in stir zone was lower than others, fatigue fracture was thought to initiate from the cavities in this case. Figure 10 shows SEM micrograph of the fracture surface on the non-heat treated specimen fractured at boundary between TMAZ and BM as shown in Fig.4(a). Dimples are dominant on the fracture surface.

On the other hand, SEM micrograph of the heat treated specimen near the fracture surface in A6063 is shown in Fig. 11. Figure 11(a) is a macroscopic view, and a lots of small chips and some

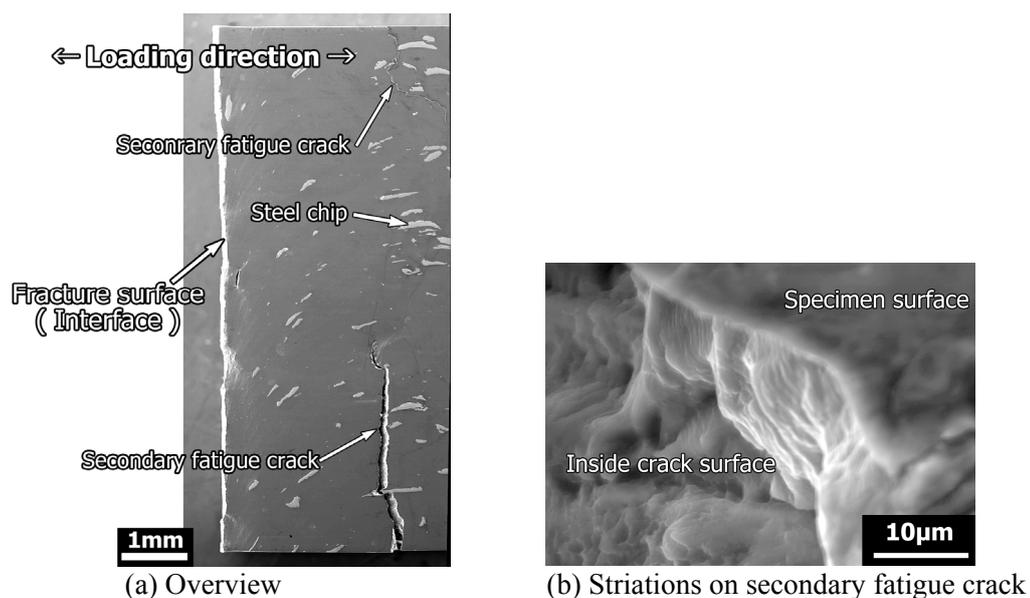


Fig. 11 SEM micrographs around fracture surface of the heat treated specimen.

(σ_a : 60MPa, N_f : 4.06×10^4)

cracks are found. In the FSW process performed in this study, S45C on the welding interface was slightly removed by probe of FSW tool. From the previous studies^{[4][5]}, it was clarified that removed steel was distributed in Al alloy as small chips but the strength of the joint was not affected by steel chips significantly. Figure 11(b) is a close up of the crack observed in Fig. 11(a). Since some striations are found on crack surface, these kind of cracks are thought to be the secondary fatigue cracks.

In this study, FSW condition was same for all specimens, however fatigue fracture modes and strengths were not necessarily similar or same level. Some environmental factors, for example temperature, humidity and so on during FSW process may affect the quality or properties of the joints, and this should be investigated in detail. Furthermore, there is a report that heat treatment of the dissimilar joint make the compound layer on the welding interface thicker and strength of the interface may become weak^[14]. Since the thickness of compound layer, i.e. strength of the interface depends on heat treatment condition, further investigation will be need.

4. Conclusions

The butt dissimilar joints of Al-Mg-Si alloy JIS A6063 and carbon steel JIS S45C by means of friction stir welding were prepared for investigating fatigue properties of the joints. And the effect of heat treatment on fatigue properties of the dissimilar joints was also investigated. The main results obtained are summarized as follows:

1. There was lower hardness region near the interface in A6063, and the hardness of this region was recovered by the heat treatment which is similar to the condition of aging process in T6 treatment for A6063.
2. The average tensile strength of the non-heat treated specimen was approximately 140 MPa and that of the heat treated specimen was 195 MPa which was about 40% improvement compared with that of the non-heat treated specimen.
3. Three types of fatigue fracture modes occurred in case of the non-heat treated specimen. The first one was fracture at boundary between lower hardness region and base material in A6063, the second type was fracture initiated in stir zone and the last one was fracture at welding interface. Since the fatigue fracture initiated at cavities in the stir zone, fatigue strength in case of the second one was lower than others.
4. Fatigue fracture was initiated at welding interface in all case of the heat treated specimen, and fatigue strength was improved approximately 25% as compared with that of the non-heat treated specimen.

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