EFFECT OF THE POST WELD HEAT TREATMENTS ON THE FATIGUE CRACK GROWTH BEHAVIOR IN FRICTION STIR WELDING OF A HEATTREATABLE ALUMINUM ALLOY

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Abstract

The effect of the post weld heat treatments (PWHTs) on the fatigue crack growth (FCG) behavior in the welded zone of AA6063-T5 fabricated by the friction stir process was investigated. The FCG specimens are machined in which the loading axis is put perpendicular to the welding line and the initial notches are introduced in the welded zone. The experimental results showed the FCG rates are sensitive to the PWHT solutions. The FCG resistance in the welded zone could be fully restored to that of base metal by using PWHT. While the PWHT solution solely restores the precipitates dissolved and/or coarsened during welding process has a minor effect on the FCG rates, the PWHT solution remarkably recrystallizes the grain microstructure has a significant effect here.

Keywords: *Aluminum alloy, Failure assessment, Fatigue crack propagation, Friction stir welding*

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1. INTRODUCTION

Friction stir welding (FSW) has been found to be a green technique in metal joining with high energy efficiency, environment friendliness, and versatility. This technique is suitable for joining aluminum alloys including the alloys recognized to be unweldable by traditional fusion welding methods. The basic concept of FSW process is quite simple. The rotating shoulder and probe of a non-consumable tool heat and plasticize the surrounding metal and a solid-state joint is established. It is well known that the FSW is thermo-mechanical processing and result of severe plastic deformation and microstructural changes. The welded zone possesses various inhomogeneous microstructure features and mechanical properties [1-3]. With aluminum alloy 6063, a heat-treatable alloy, the effect of temperature on the microstructure and/or mechanical properties during welding is unavoidable. In fact, during the welding process, the FSW temperature in AA6065-T5 is up to 550^{o}C [4], significantly higher than that of the dissolution point of this alloy (about 250^{o}C [5]). Otherwise, with AA6063-T5 FSW, it is possible to apply the post weld heat treatment (PWHT) solutions to improve the microstructure and/or mechanical properties of the joint [5,6]. In order to explore the effect of the PWHT solutions on the FCG rates in the welded zone of the FSW AA6065-T5, before FCG testing, the FSW specimens are treated by the PWHTs. Here two PWHT solutions are given which named PWS1 and PWS2. The former solution was by aging at 175°C/12hrs aiming to restore the precipitates dissolved and/or coarsened by welding process, and the latter was by aging at 530°C/1hr followed by quenching in water to recrystallize the microstructure and subsequent aging by 175°C/12hrs in the air to restore the precipitates dissolved and/or coarsened by the welding process [5]. In this work, the discussion is put on the comparison of the results between the as-welded condition and in the PWHT conditions and the different FCG rates among the representative locations including BM site. The tensile strength is performed by MTS machine, the hardness and residual stress in and around the welded zone are measured by a diamond indentation Vicker, and the residual stress was measured by X-ray diffraction method.

2. EXPERIMENTAL PROCEDURES

The 5.0 mm AA6063-T5 plates were butt-joined by friction stir welding using a NC milling machine. The weld tool geometry applied in this work was a scrolled shoulder tool and a truncated cone pin with the pin diameter of 5.0 mm at the middle pin length, the pin height of 4.5 mm, and the screw pitch of 1.0 mm. The pin was aligned at a tilt angle of 2.0 deg. in the plane containing the pin axis and center weld line. The tool tip was kept at a distance of 0.2 mm from the backing anvil. Various regimes of weld parameters were performed by combining the tool rotation speed and the weld speed. An optimized FSW joint was selected by relying on its highest tensile properties and was used to conduct the FCG tests. From a 5.0 mm FSW plate, the center-notched fatigue specimens were extracted, the loading axis of the fatigue test and the crack propagation direction are transverse and longitudinal to the welding direction, respectively (Fig. 1). In order to investigate fatigue crack growth behavior which must be sensitive to the propagation area, an initial notch of each FCG specimen was introduced at each objective area in the joint by electro discharge machining, as illustrated in Fig. 1. The length and radius of notch are 7.0 mm and 0.1 mm, respectively. In the specimens named SZ, MZ, and BM, the notch is located at the center of the stirred (or welded) area, at 5.0 mm apart from weld center, and base metal site, respectively.

The fatigue tests were conducted for both the as-welded and PWHTed FSW specimens at room temperature in laboratory air and 25Hz load frequency with loading ratio R=0.1 by means of a servo-hydraulic testing machine, followed the **ASTM E647** standard [7]. The length of cracks was monitored from both sides of the specimen surface by means of a traveling microscope. Residual stress in and around the welded zone was measured by X-ray diffraction (XRD) $\sin^2\psi$-method, following the Standard Method for X-ray Stress Measurement proposed by The Society of Materials Science of Japan [8]. Residual stress measurements were collected at a Bragg angle of 139.5 deg. Corresponding to diffraction at the {311} planes. The hardness in and around the welded zone of as-welded and tested specimens was measured by a diamond indentation with 50g loading and 10 seconds hold time. The tensile tests were performed by the MTS hydraulic machine at a constant strain rate of 10^{-3}/s. The microstructure was observed by scanning electron microscope (SEM).

3. EXPERIMENTAL RESULTS AND DISCUSSION

After fabricated, the welds are mechanically polished and chemically etched to observe the microstructure in and around the welded zone. The microstructure and the hardness in the weldment of the as-welded FSW are displayed in Figs. 2&3. Figure 2 shows that the joint possesses a very inhomogeneous feature. The grain size in the stirred zone (Fig. 2b&c) is quite fine compared to that outside the stirred zone (Fig. 2a&d). The hardness across the weld is measured at the midline as shown in Fig. 2. Obviously, in Fig. 3, the MZ and SZ in the as-welded FSW possessed significantly lower hardness than other areas (see circle symbols in Fig. 3). The softening was believed to be associated with the coarsening and/or dissolution of precipitates in this alloy [5]. After applying the PWS1 or PWS2, the hardness in and around the welded zone was mostly restored to that of BM. The hardness distributions across the welding in the treated PWS1 and PWS2 specimens were shown in Fig. 3 (see the square symbols and triangle symbols, respectively). In the microstructure aspect, whilst the grain size in the welded zone of the PWS1 specimen was seen to be comparable to that of the as-welded FSW specimen, the grain size in the welded zone of the treated PWS2 specimen was coarsened significantly as seen in Fig 4.

The residual stress was measured in a diffracted area of 2×2 mm^2 on specimen surface after electrochemical polished. Attention was paid to MZ and SZ where correlate with the FCG areas. Here the residual stress component which parallels to the fatigue loading direction is measured. The residual stress at MZ and at SZ is quite small and compressive, -12.8 MPa and -1.5 MPa, respectively.

All results of the FCG tests at SZ and at MZ in the FSW under both as-welded and PWHT conditions are presented in Fig. 5 through Fig. 10. Here, each figure shows the relationship between FCG rate, *da/dN*, and stress intensity factor range, ΔK. It can be seen the FCG behavior is sensitive to the PWHT solutions.

The FCG rates at SZ and MZ in the as-welded were shown in Fig. 5 and Fig. 6, respectivelly. Here, the rates at both SZ and MZ are about haft order higher than those of BM. From this view, it means that the welded zone possessed a weak FCG ressistance in comparing with BM. An intergranular fracture mode was found on the fracture surface [9]. In addition, it also can be seen from these two figures that FCG rates at MZ and at SZ seem to be comparable (Fig. 7).

The results of the FCG rates in the MZ specimen treated by PWS1 are shown in Fig. 8 (in comparison with the as-welded MZ). Here the FCG rates in the MZ under the PWS1 treated condition and the as-welded condition are quite similar. It means that the FCG resistance in the MZ seems to be improved insignificantly after treated by the PWS1. The results can be seen clearly in Fig. 9.

It should be noted that the dissolution and/or coarsening precipitates in the virgin FSW are believed to be mostly restored after using PWS1 as mentioned above. In addition, the grain size in and around the weldment was found to be unchanged after treated by PWS1. Furthermore, the residual stress at the MZ in the as-welded is small and compressive (-12.8 MPa) and to be released unremarkable by the PWS1 treatment solution (it is released about 4 percent). From three points of view, it provides an important view that the restoration of the precipitates in the welded zone seems to have a tiny effect on improving the FCG resistance in the welded zone.

Now the effect of PWS2 on the FCG rates in the joint is considered. The FCG rates at SZ in the FSW specimen treated by PWS2 are presented in Fig. 10, in comparing with the results of the as-welded FSW. Here the FCG rate at the SZ treated by PWS2 is about haft order lower than that of the as-welded SZ. Obviously, the FCG resistance at SZ is improved remarkably after treated by PWS2 and it is mostly restored to the BM (see Fig. 10). The significant improvement of FCG resistance after applying the PWS2 is expected concerning to the remarkable recrystallization of the microstructure in the welded zone by this treated solution, in which the coarsening microstructure is one of evidences (see Fig. 4).

From the results found in the PWS1, the role of the restored precipitates in the PWS1 has a minor effect on the FCG rates. Moreover, the residual stress at SZ in the as-welded FSW was found to be very small and compressive (-1.5 MPa). This value of the residual stress is believed to have a minor effect on the FCG rate at SZ in the both as-welded FSW and PWS2-treated FSW. These points of view could be inferred the fact of that the recrystallization of microstructure in the welded zone after applying the PWS2 had an important role in improving the FCG resistance of the joint in which the regeneration of grain boundaries in the welded zone is expected to be critical here. It is interesting that, commonly, the FCG resistance is improved by the grain boundaries as the barriers [10, 11], however, in this case it shows an opposite manner, here the FCG resistance is increased when the grain sizes are coarsened. This abnormal phenomenon could be concerned about the fact that the grain boundaries in the stirred zone are weakened by the stir welding process and this issue is extricated by applying PWS2 solution.

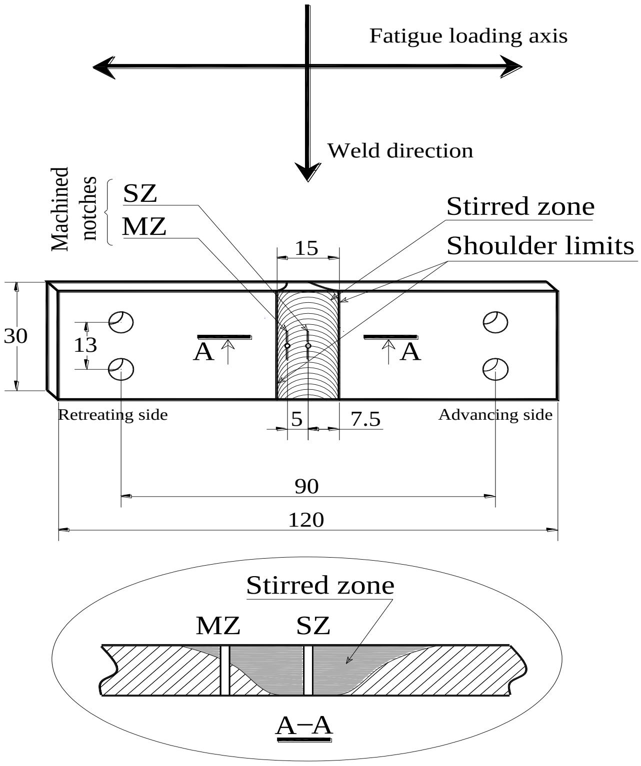

Fig – 1: Geometry of specimen used and the notch locations.

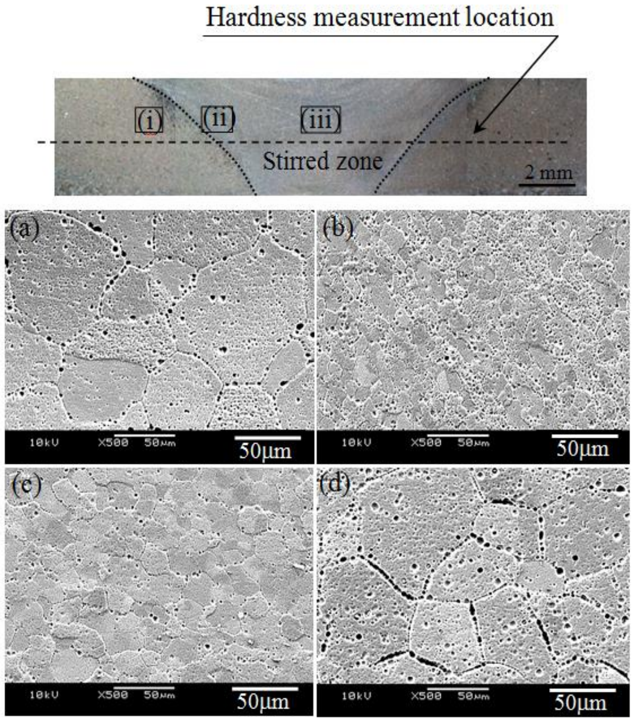

Fig – 2: Microstructure in the cross section (a) region (i), (b) region (ii), (c) region (iii), and (d) base metal.

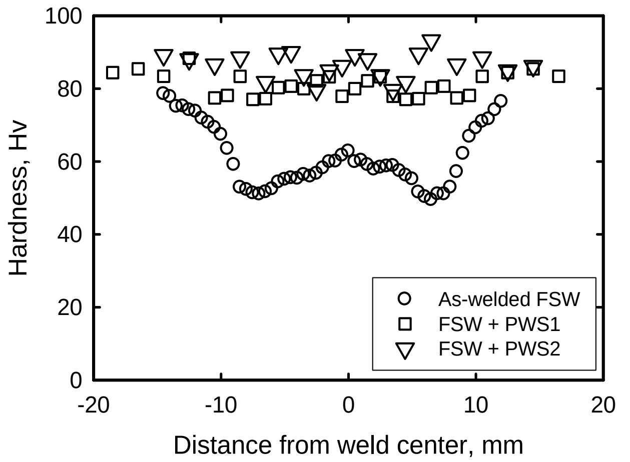

Fig – 3: Hardness distributions in FSW under different conditions.

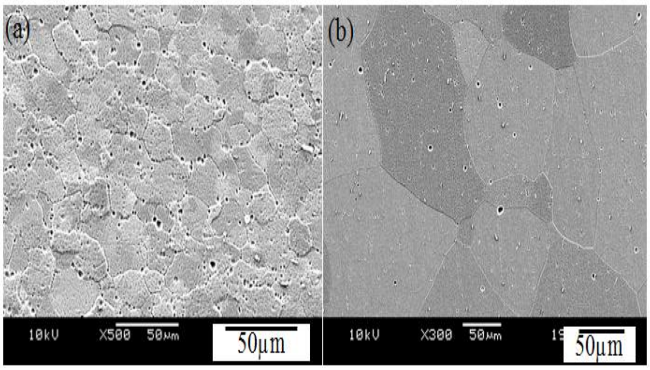

Fig – 4: Microstructure in the stirred zone (a) as-welded FSW and (b) after PWS2.

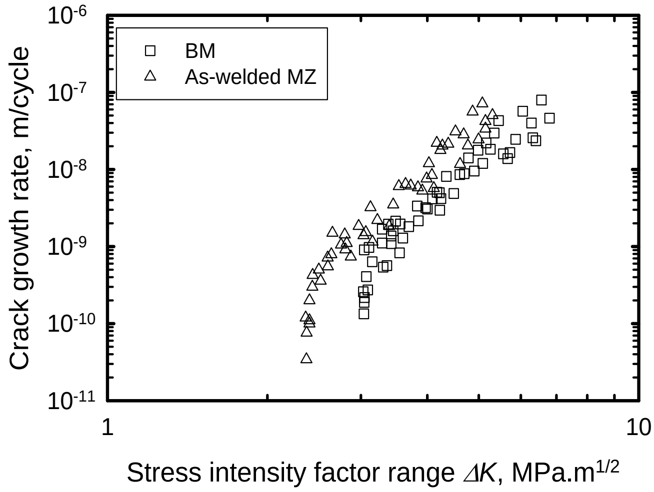

Fig – 5: Fatigue crack growth rates at the MZ of the as-welded FSW.

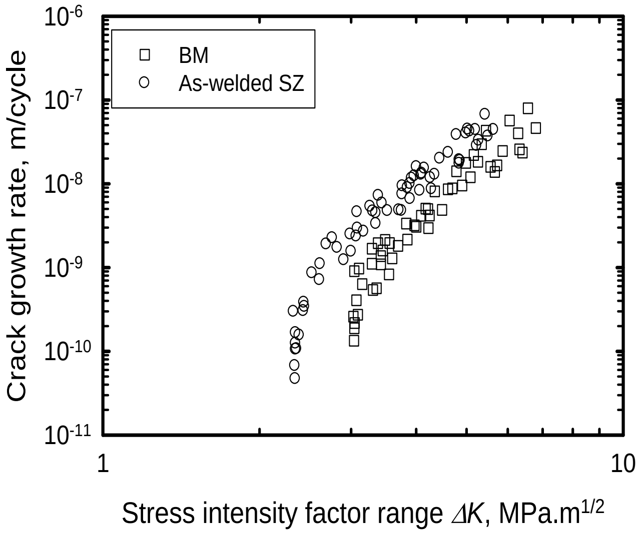

Fig – 6: Fatigue crack growth rates at SZ of the as-welded FSW.

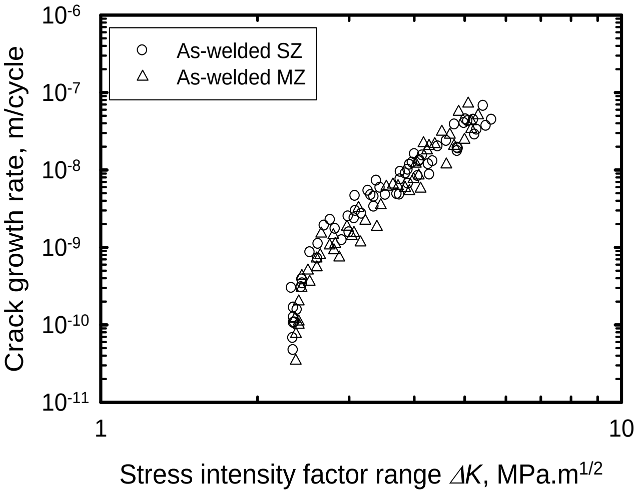

Fig – 7: Fatigue crack growth rates at the MZ of the as-welded FSW.

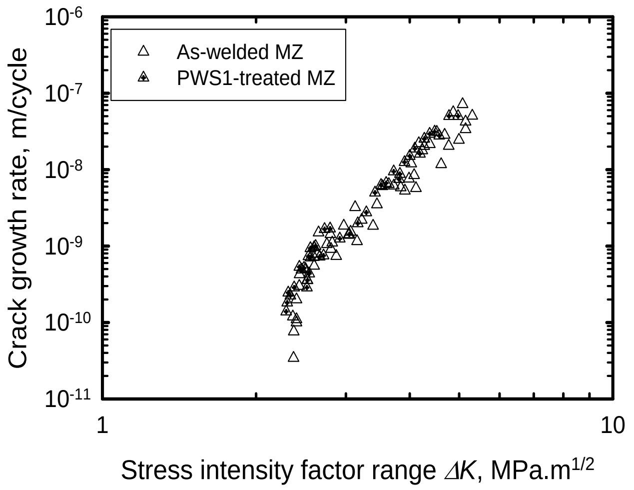

Fig – 8: Fatigue crack growth rates at MZ of the FSW treated by PWS1.

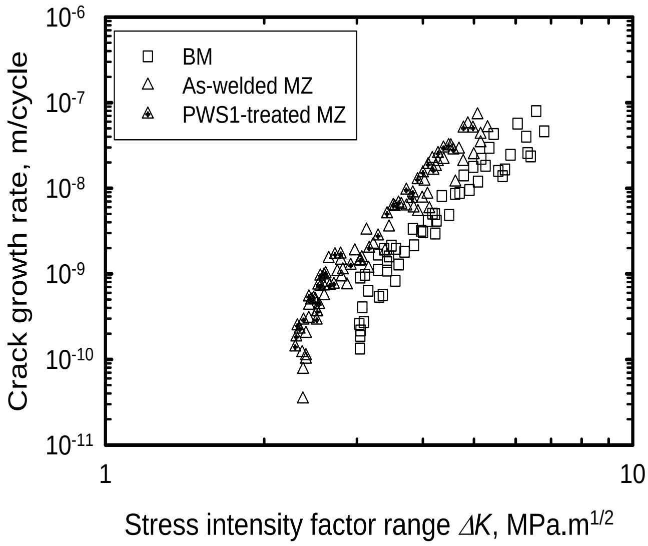

Fig – 9: Fatigue crack growth rates at the MZ.

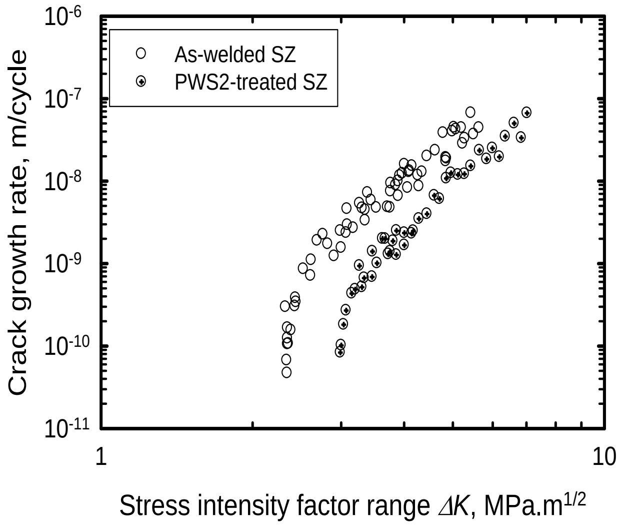

Fig – 10: Fatigue crack growth rates at SZ of the FSW treated by PWS2.\

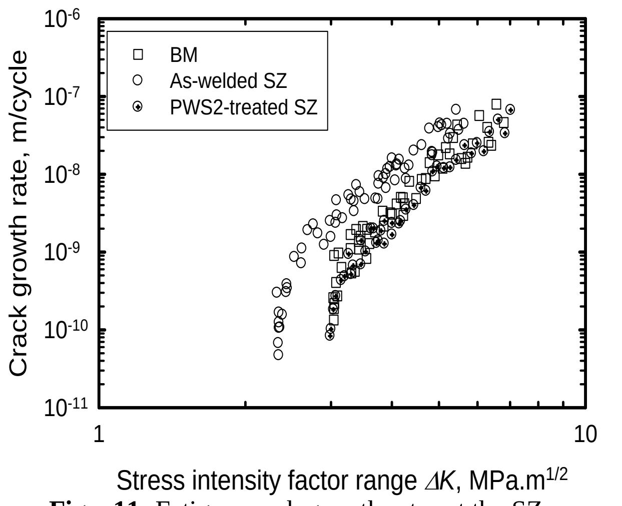

Fig – 11: Fatigue crack growth rates at the SZ.

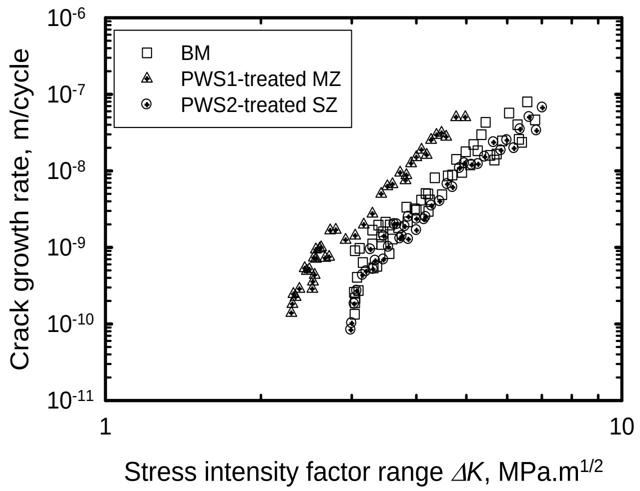

Fig – 12: Fatigue crack growth rates in the FSW treated by PWS1 and PWS2.

As a summary of this work, the FCG rates at SZ and MZ are found to be sensitive to the PWHTs. By using the suitable PWHT, the FCG resistance in the FSW joint can be could be enhance remarkably. Whilst the PWS1 which only restored the precipitates affected unremarkable to the FCG resistance of the FSW, the FWS2 with both restored the precipitates and recrystallized the welding microstructure influenced significantly to the FCG resistance of the FSW joint and it is fully restored to that of BM.

4. CONCLUSION

The FCG resistance in the friction stir welding zone is lower than that of base metal. The FCG resistance in the welded zone could be improved and restored to that of the base metal by applying the PWHT solution. In two PWHT solutions applied here, whilst the PWS1 has a tiny effect on the improvement the FGC resistance in the joint, the PWS2 shows a remarkable improvement and the FCG resistance become fully restored to that of base metal even though this PWHT solution reduced remarkably the grain boundary barriers. This study found the important points that the role of the restored precipitates has a minor effect on improving the FCG resistance in the FSW. The recrystallization of welding microstructure is found to have a critical effect here.

ACKNOWLEDGEMENTS

I am grateful to Prof. Masakazu Okazaki for several hours of his advices. I also thanks to prof. Kenji Suzuki for his residual stress measurement support.

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