HEAT INPUT AND POST WELD HEAT TREATMENT EFFECTS ON REDUCED-ACTIVATION FERRITIC/MARTENSITIC STEEL FRICTION STIR WELDS

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Abstract

Reduced-activation ferritic/martensitic (RAFM) steels are an important class of structural materials for fusion reactor internals developed in recent years because of their improved irradiation resistance. However, they can suffer from welding induced property degradations. In this paper, a solid phase joining technology friction stir welding (FSW) was adopted to join a RAFM steel Eurofer'97 and different FSW parameters/heat input were chosen to produce welds. FSW response parameters, joint microstructures and microhardness were investigated to reveal relationships among welding heat input, weld structure characterization and mechanical properties. In general, FSW heat input results in high hardness inside the stir zone mostly due to a martensitic transformation. It is possible to produce friction stir welds similar to but not with exactly the same base metal hardness when using low power input because of other hardening mechanisms. Further, post weld heat treatment (PWHT) is a very effective way to reduce FSW stir zone hardness values.

Introduction

An extremely hostile environment exists inside fusion reactors, such as intense heat flux, significant cyclic thermo-mechanical stresses, intense flux of high-energy neutrons, electromagnetic radiation, and reactive chemicals. Reduced-activation ferritic/martensitic (RAFM) steels were developed in recent years and are considered as the most promising structural material for use in a fusion reactor to resist damages because of the aggressive environment [1-3]. However, when joining RAFM steels with traditional fusion welding technologies, such as tungsten inert gas (TIG) welding, electron beam welding and laser welding, significant strength deterioration occurs due to the development of δ-ferrite and precipitate dissolution in the welded joint [4]. To solve this weld properties degradation, a solid phase joining technology friction stir welding was adopted to join RAFM materials of Eurofer'97 plates [3] and F82H thin sheets [2]. Hardness, similar to the base metal, was obtained by post weld heat treatment and by using a low tool rotation rate. In this paper, 7.9 mm thick Eurofer'97 plates were friction stir welded with different tool rotation rate/heat inputs. Defect free welds were obtained with multiple FSW parameter sets. FSW heat input, stir zone microstructure, weld zone microhardness and the influence of heat input in material structures and properties are discussed.

Experimental procedures

The workpiece material is a RAFM steel Eurofer'97. General chemical composition (wt. %) of this material is: 0.11C, 8.7Cr, 1W, 0.10Ta, 0.19V, 0.44Mn, 0.004S, balance Fe [1]. Plates to be welded are about 7.9 mm in thickness. All FSW processes were carried out on the ORNL FSW process development system (PDS) using a PCBN tool with a 25.4 mm diameter convex shoulder and a 6.5 mm long tapered pin. Except for one butt joint weld, all other trials were bead-on-plate. Weld parameters included three sets of tool rotation rates in coordination with welding speeds of: 400 rpm and 50.8 mm/min, 200 rpm and 50.8 mm/min, and 100 rpm and 25.4 mm/min. All FSW was carried out with position control. FSW response parameters such as resistance force and torque were recorded by the control computer.

After FSW, two metallographic specimens were cut from each weld and one specimen of each condition was post weld heat treated (PWHT) at 760°C X 1 hour + air cool. This heat treatment is similar to the Eurofer'97 base metal temper treatment (760°C X 1.5 hours [1]). The only difference is the high temperature time duration.

All of the as-welded and PWHT specimens were ground, polished, and etched for microstructural observation under an optical microscope. Vickers microhardness was performed on metallographic specimens along weld midplanes. Microhardness testing was completed using a 500 g load for 15 seconds of loading time and a 0.25 mm spacing between indentations.

Results and Discussion

Welds of all conditions are shown in Figure 1. The first two conditions, 400 rpm and 200 rpm tool rotation rates, performed quite well, and no FSW defect was observed from the top surfaces or exit holes. The third condition, 100 rpm, required higher torque than the machine could provide without the gear reduction box installed. Therefore, the tool rotation stopped and the FSW tool pin failed after less than 10 mm of travel. The tool may not fail if the machine can supply sufficient driving torque after the gear reduction box is installed.

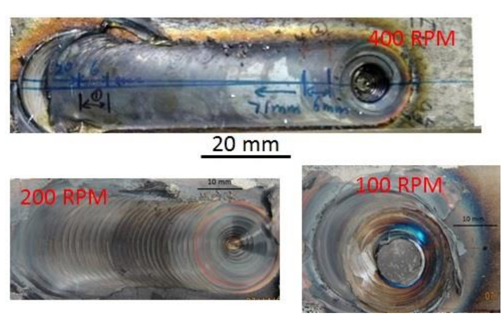

Figure 1. Eurofer'97 friction stir welds made with different parameters.

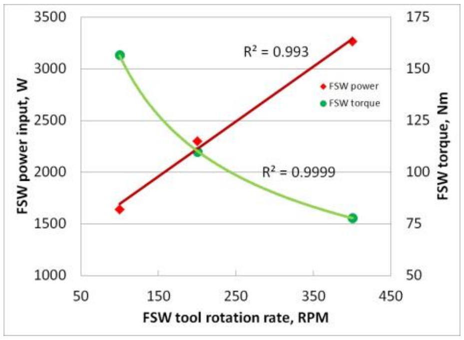

Figure 2. FSW torque and power in various conditions.

In the successful FSW trials, torques and power inputs presented the same trends with previous FSW research results, i.e., torque decreases and power increases with increasing tool rotation rate, Figure 2. In addition, very good power and linear curve fittings can be applied to these experimental results. Previous studies showed a power plateau when the tool rotation rates reach certain values at the high end. The trends may be the same here, but tool rotational speeds used here were not high enough to demonstrate this power plateau.

Base metal and stir zone center microstructures of different welds are shown in Figure 3. Similar to the as-received condition in other publications [1, 2], the base metal has a fully martensitic structure with lath-shaped martensite subgrains. However, with the FSW heat input, grain structure may change dramatically. For the high power input case (400 rpm tool rotation rate), grain size was larger, conversely, for the low power input case (100 rpm tool rotation rate), grain size was similar to the base metal, though the metallographic sample was very close to the FSW tool plunge location and definitely was affected by the plunge heat input.

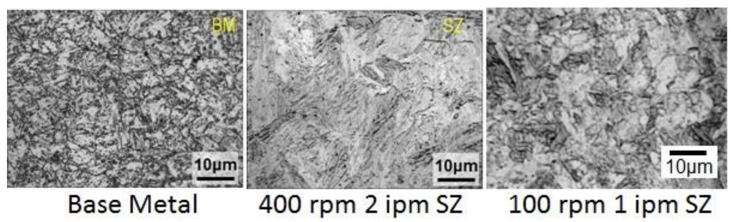

Figure 3. Microstructure of Eurofer'97 base metal and stir zone of FSW made with different heat input.

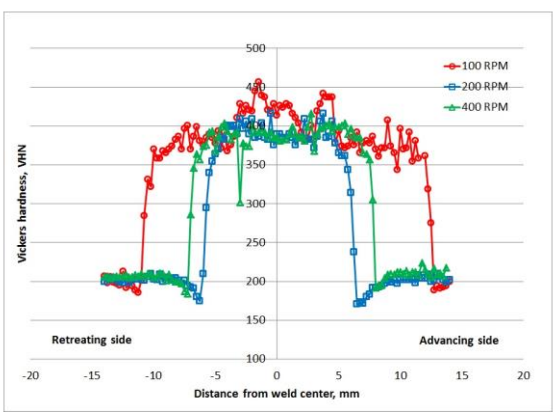

Figure 4. Microhardness of welds made with various tool rotation rates.

Vickers hardness distributions along the stir zone midplane of three power input FSW are shown in Figure 4. The FSW heat input raised the stir zone material into the austenite region during welding with subsequent quenching to martensite during cooling resulting in the stir zone hardness for all conditions increasing from 200 VHN to 400 VHN. In the HAZ, the high power input FSW (400 RPM) resulted in a wider area than the medium power input FSW (200 RPM) because of more heat generated in the stir zone. However, the low power input FSW (100 RPM) demonstrated the widest HAZ, not because of the local heat input, but from the heat input generated during the tool plunge process. Likely, that is the cause for the higher stir zone hardness compared to the other two welds. Furthermore, the high and medium power input FSW stir zone hardness are quite uniform along the midplane lines while the low power input FSW stir zone hardness values are asymmetric distributed. Like many other friction stir welds, the minimum hardness values are located in the HAZ. On the retreating side, minimum hardness values are about the same for all parameter sets. However, on the advancing side, the medium power input FSW has a lower minimum hardness than the other two conditions, though the absolute value is close to those on the retreating side. i.e., about 25 VHN lower than the base metal hardness.

Microhardness distributions of high and medium power input FSW after PWHT are shown in Figure 5. From Figure 5, stir zone hardness decreased considerably but not quite back to the base metal level, still about 50 VHN higher than that of the base metal. In Eurofer'97 base metal, carbide precipitation, presented as Cr rich ($M_{23}C_6$) and Ta/V rich ((Ta, V)C), as well as several kinds of inclusions, such as MnS and Ta-rich inclusions, were identified by X-ray diffraction and TEM studies[1]. Therefore, the PWHT applied in this paper might reduce the martensite hardening effect caused by FSW inside the stir zone but might not ease other effects such as precipitation shapes and distribution. Moreover, the FSW heat input level affected the stir zone hardness distribution after PWHT. The high heat input FSW had higher hardness than the medium heat input FSW on the retreating side but they are almost the same on advancing side. This is a different pattern compared with the hardness distribution in the as-welded condition shown in Figure 4. This phenomenon might be caused by different thermal-mechanical processes in FSW but further studies are required to draw solid conclusions. Finally, the further temper treatment of PWHT didn't affect the HAZ minimum hardness. That is not an unexpected result considering RAFM steels are designed to resist high temperature creep.

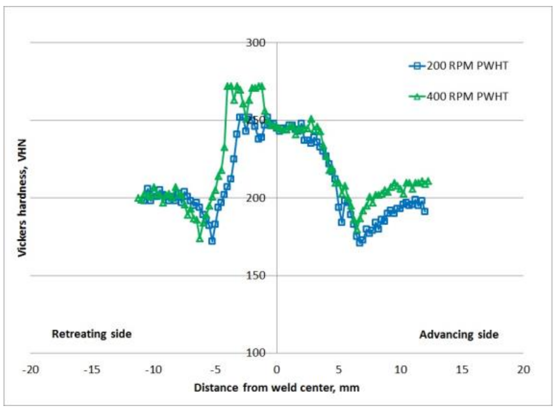

Figure 5. Post weld heat treated welds microhardness distribution

In a study carried out with another RAFM steel, F82H thin sheet (1.5 mm thick), similar hardness to base metal was realized, 240 VHN vs. 220 VHN, by using a low tool rotation rate FSW (100 RPM) without PWHT. In that investigation, uniformly distributed precipitates and very fine ferritic grains were observed in the stir zone [2]. Obviously, there are other hardening mechanisms than

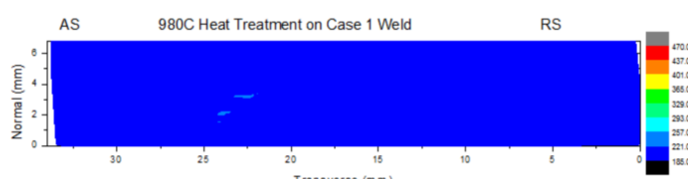

Figure 6 Microhardness of FSW and full solution and temper PWHT [3].

martensitic hardening mechanism in RAFM materials. In a previous study, a total solution + temper heat treatment was carried out with a Eurofer'97 friction stir weld, 980° X 0.5 hour + quench + 760°C X 1 hour + air cool, and a uniform hardness distribution across the welded joint was obtained [3], Figure 6. Therefore, PWHT is a very effective way to restore FSW joint mechanical properties.

Conclusions

Several hardening mechanisms exist in Eurofer'97 material, including martensitic, carbide precipitation and inclusion, and they may be all affected by FSW processes. Generally, the temperature in FSW is higher than RAFM materials austenized temperature and stir zone hardness values doubled when compared with the base metal hardness value. Conversely, very low power input FSW may weld RAFM materials with temperature lower than the Ac_1 line with medium to thick material thickness. However, even when the welding temperature is lower than the Ac_1 line, mechanical properties of the stir zone may not be exactly the same as the base metal due to other hardening mechanisms. There is a soft zone in the HAZ, and the minimum hardness value is not affected by the post weld tempering heat treatment. Finally, temper PWHT is a very effective way to decrease the stir zone hardness to a reasonable level.

Acknowledgement

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