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Impact of friction stir welding on recrystallization of oxide dispersion strengthened ferritic steel

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ABSTRACT

Oxide dispersion strengthened (ODS) steels can be used as the structural materials in the future fusion reactors and the fuel cladding materials in the advanced fission reactors. However, the weldability of ODS steels is a severe problem. In the present study, defect-free joints of the 15Cr-ODS ferritic steel were achieved by friction stir welding at different rotation speeds. The recrystallization, hardness and tensile properties are highly related with the rotation speed of the stir tool. The higher rotation speed results in coarser grains in the top SZ, while the grain size exhibits more complicated relation with the rotation speed in the SZ center. The joint welded at 250 rpm exhibits a maximum tensile strength of 974 MPa that reaches about 84% of that of the base metal.

1. Introduction

Oxide dispersion strengthened (ODS) ferritic steels, which possess high resistances to the irradiation damage and good mechanical performances at elevated temperatures, can be used as the accident-tolerant fuel (ATF) cladding for the generation IV nuclear energy systems, as well as the structural materials for advanced reactors [1–5].

In order to apply these alloys to large and complicated structures, joining is an essential and inevitable process. It has been found that conventional melting welding methods severely disturb the dispersion of the fine oxide particles in the alloy [6–8]. Since the excellent creep resistance and the neutron radiation resistance of ODS alloys are mainly due to the ultrafine and homogenously dispersed oxide particles, conventional melting welding methods are not acceptable.

Friction stir welding (FSW), which is a solid state joining process, have been considered to be a promising way to weld ODS alloys [6]. The related work concerning the FSW of high-Cr ODS steels has shown that the microstructural evolution in the joint is characterized and dominated by the continuous dynamic recrystallization (CDRX) [9–11]. The CDRX is activated and promoted by the mechanical force imposed by the stir tool. During the CDRX, the grain size [4,10,12], grain-boundary structures [9,13] and textures [10] are changed.

Wang et al. [14] found that a coarse initial grain structure (grain size in mm) of MA956 was significantly refined to 3.4 μm following FSW. However, grain coarsening in the SZ was also reported by other researchers. For example, Baker and Brewer [15] found that FSW on an initially fine grain microstructure (<1 μm) resulted in grain coarsening (>10 μm) in the stir zone. They [15] also illuminated that grain morphology following FSW was dependent on initial grain structure. As the grain morphology can be drastically changed during CDRX, the CDRX behavior plays an important role in the joint properties and determines the performance and service reliability of the structures.

So far, very limited work has been done for investigating the recrystallization in FSW of high-Cr ODS steels. The present study is aimed to clarify the effects of rotation speeds on the recrystallization in the FSW joints of high-Cr ODS ferritic steel.

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Table 1
Chemical compositions of the 15Cr-ODS ferritic steel (wt%).

Material	C	Cr	W	Ti	Y_2O_3	Fe
15 Cr-ODS	0.02	14.9	1.9	0.2	0.34	Bal

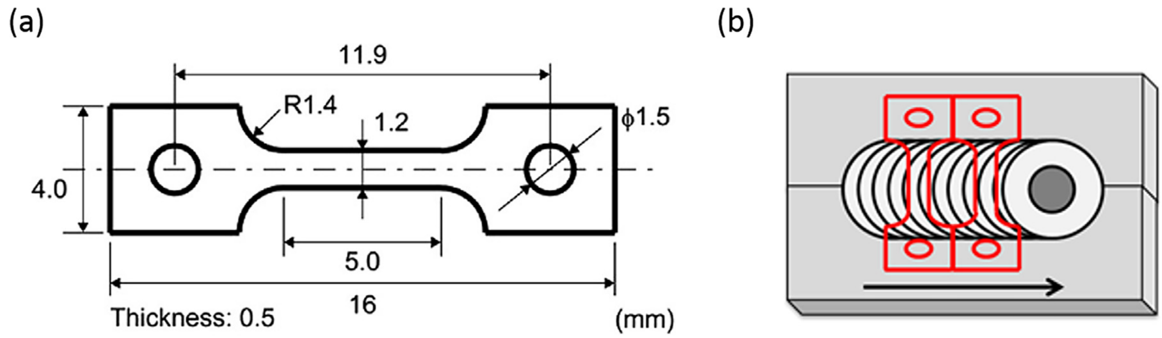

Fig. 1. Specimen for tensile tests: (a) specimen dimension; (b) cutting position of specimen in welded joint.

2. Experimental procedure

The material used was a 15Cr-ODS ferritic steel with the composition tabulated in Table 1. This material was produced by mechanical alloying (MA) where the Fe -15Cr powder was mixed with the Y_2O_3 powder. The MA process was conducted by a high-energy attritor in an argon atmosphere with the ball-to-powder weight ratio of 15:1 and the milling time of 48 h. The resultant powder was subsequently consolidated by hot extrusion and forging at 1150 °C, then annealed at 1150 °C for 1 h.

The plates were cut into specimens with dimensions of 35 × 10 × 1.5 mm, and then subjected to FSW in a butt configuration. A WC-based stirring tool with a shoulder diameter of 12 mm, a pin diameter of 4 mm and a pin length of 1.3 mm was used in the welding process. To investigate the effect of rotation speed on the hardness and the microstructure, four rotation speeds (250 rpm, 300 rpm, 350 rpm and 400 rpm) were used, with a constant traverse speed of 50 mm/min.

Vickers hardness measurements were conducted using a diamond indenter with a testing load of 200 gf, a dwell time of 10 s and an indent spacing of 0.5 mm. The tensile properties of joints were evaluated using the SS-J2-type miniaturized tensile specimens with the dimensions as shown in Fig. 1(a). The specimens were cut out from the FSW joint perpendicular to the welding direction, as shown in Fig. 1(b). The tests were carried out at room temperature at a crosshead speed of 0.2 mm/min.

Microstructures were observed by scanning electron microscopy (SEM) and electron backscatter diffraction (EBSD) on the transverse cross-section of the welds. The EBSD work was performed using a Zeiss Ultra 55 FE-SEM field emission SEM equipped with EBSD system, and the data was processed by TSL data analysis software.

3. Results and discussion

As the microstructures are drastically varied within different zones of the FSW joint, hardness tests are used to characterize the joint and provide clues of the specific locations. The hardness distributions on the transverse cross-section of joints welded at different rotation speeds are plotted Fig. 2. The hardness curves exhibit a valley-type shape, which is characterized by a decrease of hardness in the SZ. The valleys are not symmetric, especially at higher rotation speeds. In particular, the top SZ has the lowest hardness with respective to the center and bottom areas in each joint.

A representative microstructure obtained by SEM in the joint welded at 300 rpm is presented in Fig. 3. Due to the large deformation during the fabricated process, the grains in the base metal (BM) have been heavily elongated. The elongated grains have sizes of about 29 μm in the long direction and 1.3 μm in the other direction. After welding, these elongated grains are changed to the nearly equiaxed grains in the SZ, as shown in Fig. 3(b).

Besides the size change, the grain orientations within the SZ are also different from that in the BM. As shown in Fig. 4, the BM has a strong texture of (110)[001], while the grains within the SZ are almost randomly orientated. These changes in the grain morphology prove that the recrystallization happens in the SZ. Through the recrystallization in the SZ, materials can relieve the imposed energy during FSW and generate new grains. According to authors' previous findings [9,10,13], this type of recrystallization can be classified as CDRX, which is activated and promoted by the welding heat-input and particularly, the drastic plastic deformation imposed by the stirring tool. The CDRX in the SZ attenuates the strain and decreases the dislocation density [10] that can contribute to the decrease in hardness within the SZ.

Fig. 4(b) shows that SZ also consists of layered structures. The top SZ exhibits coarser grain layer of about 90 μm, and the grain size decreases with increasing the distance from the top surface. As the friction heat provided by the tool shoulder dominates the welding heat-input of FSW, the area near the top surface should have higher temperature than the inside area. The high temperature could result in the coarser grains in the top of the joint.

Another interesting and attractive phenomenon exhibited in Fig. 4b is that the finer grain layer still consists of several sub-layers, which can be distinguished and divided based on their different preferred orientations. It could be attributed to the plastic flow of the transferred metal during welding process. During FSW, the transferred metal driven by the stir tool flows layer by layer surrounding the stir tool. Inevitably, the difference of the temperature and the imposed mechanical force in the different layers, as well as the complicated interactions among different layers, can affect the final morphology of the grains in each layer, such as the grain size and the preferred orientation.

It is also remarkable that the hardness curves of Fig. 2 are asymmetric. The hardness on the left side of the plot, which is

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