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ODS ferritic steel engineered with bimodal grain size for high strength and ductility

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ABSTRACT

An attractive way to enhance the ductility of ODS ferritic steels is to develop an alloy with a bimodal grain size distribution, in which the micron-sized coarse grains provide high ductility. The nanometer-sized fine grains enhance the tensile strength. The microstructures were obtained by blending the gas-atomized powders and mechanical alloyed powders, followed by hot forging and annealing. The homogeneously distributed nanometer-sized oxide nanoparticles can also be detected. Mechanical properties tests revealed a great improvement in ductility in comparison with other ODS ferritic steels, and high strength over the whole range of test temperatures, owing to the fine grains and oxide nanoparticles. The combination of high ductility and high strength makes this ODS ferritic steel much promising in high-temperature application.

1. Introduction

Oxide dispersion strengthened (ODS) ferritic steels, used as structural applications in nuclear reactors, have drawn much attention since the 1990s, due to their excellent high-temperature tensile strength and creep resistance [1–4]. However, there are still many challenges that cannot be evaded. Particularly, as one kind of nanostructured alloys, the ODS ferritic steels usually exhibit a low tensile ductility [5–7], which may be attributed to the poor strain hardening capacity of the nanometer-sized grains. Intragranular dislocation activity is expected to be rather limited in nanocrystalline materials, so that conventional strain hardening may also be limited [8]. Recently, a bimodal grain size distribution is proposed to enhance ductility in nano- or sub-microcrystalline metals without much loss of their strength [9–12]. Witkin et al. [9] reported improved ductility in a nanostructured Al–Mg alloy by the deliberate addition of a coarser-grained fraction. Wang et al. [11] also observed ductility increase in an nanocrystalline ECAP pure Cu with micron-sized grains (1–3 μm) in a matrix of nanometer-sized grains (<300 nm). The key of the strategy is to impart work hardening ability by mixing micron-sized grains into the matrix, since there is enough space for dislocation storage in the coarse grains.

The purpose of this study is to fabricate an ODS ferritic steel with bimodal grain size distribution engineered for high strength with enhanced ductility, and to explore the mechanism on the mechanical properties.

2. Experimental

The raw powders used in this study were Fe–14Cr–3W (wt.%, same as below) gas-atomized (GA) powders, Ti and Y hydrides, and Fe_2O_3 (100 nm) particles. Mechanical alloyed (MA) powders with a nominal composition of Fe–14Cr–3W–0.3Ti–0.3Y–0.1O were produced by ball milling the raw powders for 48 h. Prior to consolidation, the GA and MA powders were blended in a weight ratio of 1:1. The blended powders were sealed and vacuumed in a steel can, and consolidated by hot forging at 1173 K. The as-forged alloy was then annealed at 1273 K for 1 h. The samples were cut from the as-annealed alloy. The microstructures were observed by using a Nova NanoSEM 230 Field Emission Scanning Electron Microscope and a FEI Tecnai G2 Transmission Electron Microscope.

The tensile specimen design chosen for mechanical tests was a small sheet type tensile specimen, with a gauge section length × width × thickness of 8 × 2.5 × 0.5 mm. Tensile tests were carried out at various temperatures ranging from room temperature (293 K) to 1023 K, with a strain rate of $2 \times 10^{-5}\ s^{-1}$, in an argon atmosphere.

3. Results and discussions

3.1. Microstructure

The microstructure of the as-annealed ferritic alloy in the transverse direction is presented in Fig. 1a. It can be seen that the as-annealed ferritic alloy has two obviously visible regions with distinct grain size distributions. One region has a grain size of 5–10 μm, and the other one consists of nanometer-sized grains with a size of 100–300 nm. Therefore, a bimodal grain size distribution has been achieved [13–15]. The estimated area fraction of the fine grain

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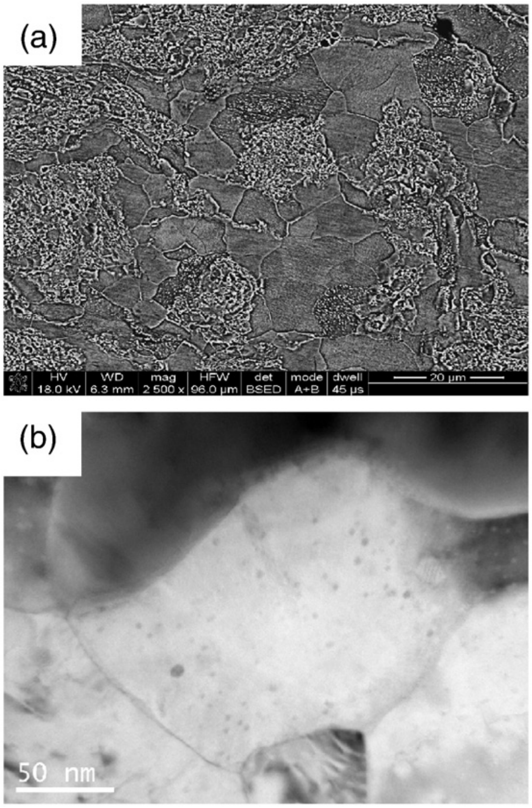

Fig. 1. Microstructure of the as-annealed ferritic alloy with a bimodal grain structure: (a) SEM image of both nanometer-sized fine grain region and micron-sized coarse grain region and (b) bright field TEM image of the nanometer-sized fine grain region.

region is about 50%, which is equal to the percentage of the MA powders in the blended powders. The formation of the nanometer-sized fine grains and the micron-sized coarse grains correspond to the MA powders and the GA powders, respectively [9].

Fig. 1b displays the bright field (BF) TEM image of the fine grain region of the bimodal-grained ferritic alloy. Oxide nanoparticles are located both intra- and intergranularly. The diameter of the oxides is about 5–10 nm.

3.2. Mechanical properties

The tensile test results of the bimodal-grained ferritic alloy as a function of test temperature are shown in Fig. 2. Fig. 2a also shows the ultimate tensile strength of other alloys: Eurofer 97 [6], ODS Eurofer (0.3 wt.% Y_2O_3) [6] and 14Cr ODS ferritic steel with unimodal microstructures [7]. It can be seen that the bimodal-grained ferritic alloy is considerably stronger than Eurofer 97 and ODS Eurofer, and the strength is only 5–15% lower than that of 14Cr ODS ferritic steel.

The influence of bimodal grain size distribution on the strength of ferritic steel can be attributed to movement of dislocations. The movement of dislocations initiates in the coarse grains earlier than the nanometer-sized fine grains, lowing the yield stress. However, owing to the high work hardening capacity of the coarse grains, the ultimate strength of the blended grains, is not severely weakened compared to the nanocrystalline 14Cr ODS ferritic steel with unimodal grain size distribution [10].

As shown in Fig. 2b, the total elongation of the as-annealed alloy increases with increasing test temperature. The total elongation of the bimodal-grained ferritic alloy is comparable to those of Eurofer 97 and ODS Eurofer from room temperature to 723 K. In comparison with 14Cr ODS ferritic steel, the elongation of the bimodal-grained ferritic alloy increases by 60–180% over the whole temperature range.

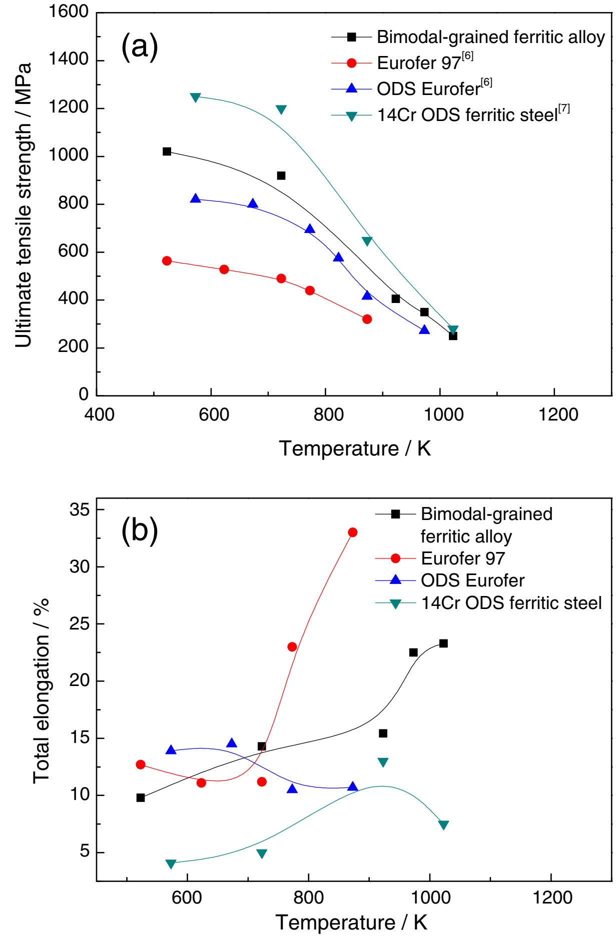

Fig. 2. Mechanical properties of the bimodal-grained ferritic alloy: (a) ultimate tensile strength vs. test temperatures and (b) total elongation vs. test temperatures.

It has been confirmed by Wang et al. [11] that the micron-sized coarse grains have excellent dislocation storage capacity and significant work hardening ability. Accordingly, much higher ductility may be achieved by incorporating of the micron-sized grains into the ultrafine-grained matrix.

A brief calculation of tensile strain demonstrates the dramatical ductility enhancement of the bimodal-grained ferritic alloy compared to 14Cr ODS ferritic steel. The maximum tensile strain of ferritic low C steels predicted by the model for unimodal or bimodal grain size distributions can be fitted to the equation below [10]:

$$\varepsilon \approx \frac{\varepsilon_{\max}}{1+L\left(\frac{d_{aver}}{b}\right)^{-1/2}} \tag{1}$$

where ε is the tensile strain, ε_{max} is the limit maximum tensile strain for certain composition, d_{aver} is the average grain size of the alloy, b is the length of Burgers vector (0.2876 nm for ferrite) and the parameter L is of the order of 200.

Consequently, the relationship between the tensile strain of the bimodal-grained ferritic alloy and 14Cr ODS ferritic steel can be given as:

$$\frac{\varepsilon_{bi\,\mathrm{mod}\,al}}{\varepsilon_{uni\,\mathrm{mod}\,al}} \approx \frac{1+L\left(\frac{d_{aver-bi\,\mathrm{mod}\,al}}{b}\right)^{-1/2}}{1+L\left(\frac{d_{aver-uni\,\mathrm{mod}\,al}}{b}\right)^{-1/2}} \tag{2}$$

where $\varepsilon_{bimodal}$ and $\varepsilon_{unimodal}$ are the tensile strain of the bimodal-grained ferritic alloy and 14Cr ODS ferritic steel, respectively; the $d_{aver\text{-}bimodal}$ and $d_{aver\text{-}unimodal}$ are the average grain sizes, respectively.

Qiu et al. [16] proposed that d_{aver} for alloys with bimodal grain size distribution should be given by:

$$d_{aver} = \sum_{i=1}^{n} d_i \ f_{area-i} \tag{3}$$

where d_i is the grain size, and $f_{area\text{-}i}$ is the area fraction of the grains with grain size d_i.

As for the bimodal-grained ferritic alloy, Eq. (3) takes the form:

$$d_{aver-bimodal} = 0.5 \times d_{FG} + 0.5 \times d_{CG} \approx 3.875 \mu m \tag{4}$$

where d_{FG}(≈250 nm, shown in Fig. 1a and b) and d_{CG}(≈7.5 μm, shown in Fig. 1a) are the average sizes of the nanometer-sized grains and the micron-sized grains, respectively.

Further, with Eq. (4), knowing $d_{aver\text{-}unimodal}$≈250 nm [7], Eq. (2) can be easily deduced as:

$$\frac{\varepsilon_{bimodal}}{\varepsilon_{unimodal}} \approx \frac{1 + L\left(\frac{d_{aver-bimodal}}{b}\right)^{-1/2}}{1 + L\left(\frac{d_{aver-unimodal}}{b}\right)^{-1/2}} \geq 200\% \tag{5}$$

This means that the maximum tensile strain of the bimodal-grained ferritic alloy may be over 100% larger than that of 14Cr ODS ferritic steel. This approximate calculation supports the results of the total elongation displayed in Fig. 2b, and substantiates the ductility improvement by that bimodal grain size distribution.

4. Conclusion

The bimodal-grained ferritic alloy has been developed by blending gas-atomized powders and mechanical alloyed powders followed by hot forging and annealing. The microstructure consists of nanometer-sized fine grains (100–300 nm), micron-sized coarse grains (5–10 μm), and homogeneously dispersed oxide nanoparticles with size of 5–10 nm. Ascribed to the high strain hardening capacity of the coarse grains and strengthening ability of the fine grains, the bimodal-grained ferritic alloy has an excellent combination of both high strength and ductility at all test temperatures.

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