JOURNAL OF IRON AND STEEL RESEARCH, INTERNATIONAL. 2016, 23(6): 553-558

Micro-alloying Effects of Yttrium on Recrystallization Behavior of an Alumina-forming Austenitic Stainless Steel

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Abstract: Micro-alloying effects of yttrium on the recrystallization behavior of an alumina-forming austenitic (AFA) stainless steel were investigated. It was found that the grain growth kinetics of the steels doped with different amounts of yttrium (i. e. , 0, 0. 05 and 0. 10 mass% Y) could be described by an Arrhenius type empirical equation. Added Y could interact with carbon and influence the morphology of carbides both inside grains and on the grain boundaries, thus altering the grain boundary mobility and grain growth. The steel doped with 0. 05 mass% yttrium showed the highest activation energy of grain growth and the most retarded recrystallization behavior, which mainly resulted from the high density of fine carbides both inside grains and on the grain boundaries. However, excess addition of 0. 10 mass% Y induced coarsening and then lowered density of carbides, which alleviated the yttrium effects. The results also manifest that micro-alloying of rare-earth elements such as yttrium is an effective way for controlling grain growth behavior during recrystallization of AFA steels, which may have great implications on engineering applications.

Key words: alumina-forming austenitic stainless steel; yttrium; recrystallization; grain boundary migration; carbide precipitation

Development of high-performance structural materials for improving energy efficiency is urgent due to the energy crisis and environmental conservation. In particular, thermal power plants are demanding advanced steels capable for serving at higher operating temperatures and steam pressure than currently available steels[1]. Austenitic stainless steels are widely used in steam turbines, high pressure steam boilers and pipes. However, the protective Cr_2O_3-based film formed on conventional austenitic stainless steels becomes unstable at temperatures above 923 K[2], especially in water vapor, due to formation of volatile Cr oxy-hydroxides, which leads to accelerated oxidation. Recently, a family of alumina-forming austenitic (AFA) stainless steels which form an Al_2O_3-based compact protective film at high temperatures was developed[3-5], and these newly developed steels showed superior high-temperature oxidation and creep resistance compared with those of conventional counterparts. Research on the new AFA stainless steels has been mainly focused on composition optimization, creep resistance, and oxidation behavior[5-9]. For engineering applications at elevated temperatures, nevertheless, high microstructural stability is also a key aspect[10,11], and a proper grain size is required to ensure superior crack growth resistance and creep rupture life[12]. Hence, grain growth behavior during recrystallization of the AFA steels has to be carefully controlled to achieve desirable overall properties[13].

Yttrium dopants have been applied in steels to improve oxidation resistance, tensile strength and rupture life at elevated temperatures[6,14], and the relevant effects are associated with refinement of grain

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Foundation Item: Item Sponsored by National Natural Science Foundation of China (51531001, 51422101, 51371003, 51271212); 111 Project (B07003); International Science and Technology Cooperation Program of China (2015DFG52600); Program for Changjiang Scholars and Innovative Research Team in University of China (IRT_14R05); Fundamental Research Fund for the Central Universities of China (FRF-TP-15-004C1, FRF-TP-14-009C1); Top-Notch Young Talents Program of China

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size and purification of grain boundaries[15-17]. Nevertheless, effects of yttrium on the grain growth behavior of the AFA steels have not been well addressed. In the current work, effects of yttrium addition on recrystallization kinetics of a typical AFA stainless steel were investigated, and the hints to achieve a controllable and homogenous microstructure were derived.

1 Experimental

Ingots with different amounts of yttrium addition (i. e., 0, 0.05 and 0.10 mass%) based on the Fe-25Ni-18Cr-3Al alloy (see detailed compositions in Table 1) were prepared by arc-melting with a non-consumable tungsten electrode in a high-purity argon atmosphere using commercially pure elements (purity above 99 mass%). The ingots were re-melted for 10 times to ensure chemical homogeneity, and then drop-cast into a 15 mm × 15 mm × 100 mm copper mold. The as-cast bars were homogenized at 1563 K for 24 h, 45% cold-rolled and then annealed at 1473, 1503, 1533 and 1563 K for 0.5, 1, 2 and 4 h, respectively, to obtain a variety of grain sizes, and subsequently water-quenched to room temperature. To clearly reveal the austenite grain boundary, the specimens with a dimension of 10 mm × 5 mm × 1.5 mm were first aged at 1023 K for 10 h, mechanically polished and then electrochemically etched at 333 K and 2.4 V in an electrolyte containing 60 vol.% phosphoric acid, 15 vol.% sulfuric acid and deionized water. Grain sizes of the alloys were examined by a 4XCE optical microscope (OM) and estimated from micrographs using the conventional mean-linear-intercept method. At least three hundred grains were measured for each grain size value. Microstructures were examined by SUPRA-55 scanning electron microscope (SEM), Tecnai F30 transmission electron microscope (TEM) and Rigaku Dmax-RB X-ray diffraction (XRD) with CuKα radiation.

Table 1 Nominal compositions of representative alloys investigated mass%

Alloy	Ni	Cr	Al	Si	Nb	Mo	C	B	P	Y	Fe
0Y	25	18	3.0	0.15	1.0	1.5	0.1	0.01	0.04	0	Balance
0.05Y	25	18	3.0	0.15	1.0	1.5	0.1	0.01	0.04	0.05	Balance
0.10Y	25	18	3.0	0.15	1.0	1.5	0.1	0.01	0.04	0.10	Balance

2 Results and Discussion

2.1 Grain growth behavior during recrystallization of steels with and without yttrium additions

All the steels added with a different amount of Y were first cold rolled and typical microstructure of the as-rolled AFA steel with 0.10 mass% Y is shown in Fig. 1(a). Austenite grains were elongated along the rolling direction and numerous deformation bands were formed inside the grains. Subsequently, all the specimens were recrystallized at different temperatures for various holding time spans. As an example, microstructural evolution of the AFA specimen micro-alloyed with 0.10 mass% Y annealed at 1533 K for different annealing time periods is shown in Figs. 1(b)-1(d). As can be seen, the large elongated grains transformed to small equiaxed grains, and the deformation bands disappeared in these annealed specimens. The grain size increased with increasing annealing time period, indicating the occurrence of recrystallization.

Representative morphology of the alloys doped with a different amount of yttrium (i. e., 0Y, 0.05Y and 0.10Y) annealed at 1473 K for 0.5 h is shown in Fig. 2. At the given temperature and time, all the Y-containing alloys have a smaller grain size than the base alloy with no yttrium addition, while the 0.05Y alloy has the smallest grain size, indicating distinct effects of yttrium on recrystallization of the AFA steels. It is clear that addition of 0.05 mass% yttrium is most effective in slowing down grain growth during recrystallization of the current AFA steel.

2.2 Kinetics of grain growth during recrystallization of AFA steels

To quantitatively evaluate the grain growth kinetics during recrystallization of the current AFA steels, average grain size of all three steels annealed under different conditions was examined by the conventional mean-linear-intercept method and the results are shown in Fig. 3. Interestingly, at any given annealing temperature and time, alloy 0.05Y always exhibits the smallest average grain size. It was found that the kinetics of isothermal grain growth of austenite grains in the current steels could be described by the empirical equation[13]:

$$d-d_0=Kt^m \tag{1}$$

where, d is the momentary average grain size; d_0 is the initial grain size; t is the holding time; and m is a time exponent during grain growth process depen-