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Phenomenological and microstructural analysis of intermediate temperatures creep in a Ni–Fe-based alloy for advanced ultra-supercritical fossil power plants

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ABSTRACT

A newly developed Ni–Fe-based alloy with high-creep strength and low cost has been developed and evaluated as the promising candidate boiler materials for 700 °C advanced ultra-supercritical coal-fired power plants applications. Three electron microscopy characterization methods–scanning electron microscopy and transmission electron microscopy and high-resolution transmission electron microscopy –were combined to obtain new insights into the microstructural and fracture surface characteristics after creep rupture tests at intermediate temperatures. The alloying elements distribution characteristics have been investigated at nanoscale through EDS mapping, especially Fe element. Fractographic analysis has been also conducted with the finding that the fracture mechanism of the crept specimens at 700 °C/300 MPa and 750 °C/150 MPa are intergranular fracture model. Dislocation configurations resulting from the creep deformation have been also performed on the crept specimens. At 700 °C/300 MPa, Orowan process combining climb of a/2 <110> matrix dislocations was dominant mechanism. At 750 °C/150 MPa, the dominant mechanism is Orowan process combining slip of a/2 <110> matrix dislocations and γ' precipitates shearing. The formation α-Cr precipitation during the creep process could act as obstacle to impede the dislocation gliding and thus increase the creep strength.

1. Introduction

Increasing energy demands as well as a desire for reductions in carbon dioxide (CO_2) emissions have led to the development of a new generation of coal-fired advanced ultra-super critical (A-USC) steam boilers for electrical power generation. It is projected that A-USC boilers, operating at 700 °C and 37.5 MPa will achieve above 50% process efficiency over current generation plants and are expected to release 40–50% less CO_2 than current generation boilers [1–3]. Decreased emissions and increased energy efficiency can be attained through increasing both the steam temperature and pressures within the boiler. Therefore, such boilers require materials that are able to provide years of service at high temperatures and pressures in harsh environments (i.e. 100,000 h creep-strength greater than 100 MPa at 750 °C and 200,000 h coal-ash corrosion resistance of less than 2 mm metal loss [4]). Novel materials, such as advanced ferritic and austenitic steels, Ni-based superalloys and thermal barrier coatings, have contributed significantly to increase the efficiency of fossil-fueled power plants for reducing the emission of greenhouse gases and improving energy conservation [5–9]. While, ferritic and austenitic stainless steels currently used in boiler applications do not have sufficient creep or oxidation resistance and cannot perform well in harsh A-USC boiler environments. Then, attention has turned to the γ' precipitation strengthened Ni-based superalloys, which are thought to be the promising candidates for high temperature components in the most severe regions of A-USC power plants, such as Inconel 740/740H (Ni–25Cr–20Co-0.5Mo–2Ti–2Nb-0.9Al, wt%) [5,10], CCA 617 (Ni–22Cr–11Co–3W–8Mo-1.2Al, wt%) [6,11,12], Haynes 282 (Ni–20Cr–10Co-8.5Mo-2.1Ti-1.5Al, wt%) [7] and Nimonic 263 (Ni–20Cr–20Co–6Mo–2Ti-0.6Al, wt%) [8]. These Ni-based alloys have good long term creep strength and good corrosion resistance. According to the reported results, Inconel 740H and Haynes 282 have higher rupture strength at 700 °C with rupture life of 100,000 h [13]. However, they are prohibitively expensive due to a

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high content of Co (10–20 wt %) and/or Mo and W (6–8 wt %).

Recently, a low cost, high creep strength Ni–Fe-based has been developed at National Institute for Materials Science (NIMS), Japan. This alloy has also attracted much attention as a promising candidate material for using as 700 °C A-USC boiler tubes. It is a γ'-precipitation strengthened alloy and the volume faction of γ' phase after aging treatment is around 20%.

The creep rupture strength of materials used within the boiler, specifically steam header piping and super heater tubes, is particularly important. In order to identify the materials that could be used within A-USC environments, stress rupture tests can be performed at different temperatures at 100 MPa Fig. 1 [14,15] shows the creep ruptures strength of various boiler materials that could potentially be used in A-USC boilers. The creep rupture resistance of this new alloy was much better than Ni-based candidate alloys CCA 617, Nimonic 230 and Ni–Fe-based candidate alloy GH2984. Its temperature capability with rupture life of 10^5 h at 100 MPa is roughly 758 °C, comparable with Inconel 740H (765 °C) [16]. This new alloy contains 30wt% Fe, and no Co addition. It has much lower cost and better hot workability than Inconel 740H alloy. Therefore, this low-cost Ni–Fe-based alloy is a promising material for 700°C-class A-USC power plant applications.

In order to characterize materials intended for boiler applications, a basic understanding of creep properties and predominant creep damage mechanism leading to creep fracture must be understood. The major concerns with Ni–Fe-based alloys are the fundamental deformation characteristics and the corresponding microstructural analysis during creep process at intermediate temperatures. In this study, careful identification of deformation microstructure was also performed in creep strained specimens in order to correlate the macroscopic behavior with the creep controlling mechanisms.

2. Material and experimental procedure

The nominal chemical compositions of this new developed Ni–Fe-based alloy are listed in Table 1. The cast ingot of this new developed Ni–Fe-based alloy was prepared via vacuum induction melting, followed homogenizing at 1200 °C for 24 h. Then, the ingot was hot forged and rolled at 1200 °C. Finally, a 10 mm thick plate was attained. All the creep test specimens used in this study were cut from this plate along longitudinal direction prior to heat treatment. Solution heat treatment was carried out at 1100 °C for 1 h, followed by air cooling. Aging heat treatment was conducted at 750 °C for 8 h and furnace cooling with a cooling rate of 50 °C/h to 650 °C, and then holding at 650 °C for 16 h with subsequent air cooling.

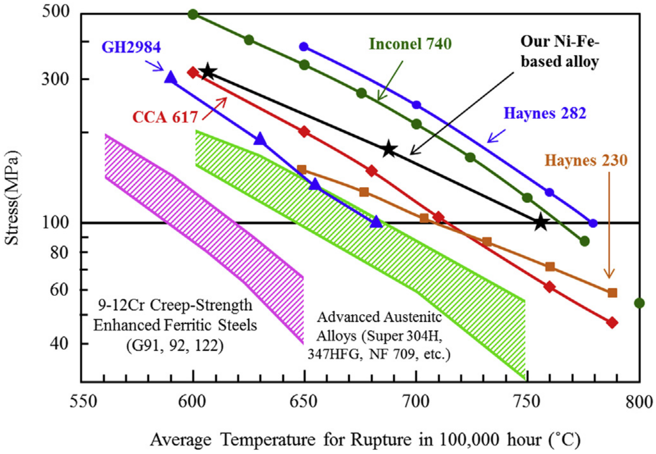

Fig. 1. Creep ruptures strength of various boiler materials that could potentially be used in A-USC boilers.

Table 1
The nominal chemical composition of the new developed Ni–Fe-based alloy.

	Ni	Fe	Cr	Mo + Nb + W	Ti + Al	Si	C	B	Zr
wt.%	Bal.	30	20	0–1.0	3.5–4.5	0.1–0.5	0.03	0.005	0.02

The creep tests of this new developed Ni–Fe-based alloy were conducted under 700 °C/300 MPa and 750 °C/150 MPa. The temperature region from 700 °C to 750 °C is of particular interest, because it is considered to be near the maximum temperature that an advanced Ni–Fe-based alloy for current generation USC power plants application can sustain for an extended period of time. After creep rupture tests, fractographic observations were performed on the tested specimens using a JSM-7001F field emission scanning electron microscopy (FESEM). Dislocations configurations resulting from the creep deformation were investigated using a Tecnai 20 transmission electron microscopy (TEM) operated at 200 kV. Elemental distribution analysis was carried out on a JSM-2100F high resolution transmission electron microscopy (HRTEM) fitted with an EDX spectrometer (operating at 200 kV). Discs of 3 mm in diameter were cut out of the tested specimens and mechanically thinned down to about 40 μm in thickness. TEM samples were prepared by a standard electro-polishing technique using a twin-jet electro-polisher. Electro-polishing was carried out at −15 °C at a voltage of 40 V, using a solution of 45 vol pct acetic acid, 45 vol pct 2n-butoxyethanol, and 10% perchloric acid.

3. Results and discussion

3.1. Mechanical response

The creep tests were conducted on this new developed Ni–Fe-based alloy at 700 °C/300 MPa and 750 °C/150 MPa, and the generated creep rate vs. time curves and creep rate vs. strain curves are shown in Fig. 2(a) and (b), respectively. As indicated in Fig. 2 (a), creep often takes place in three stages. In the initial stage, strain occurs at a relatively rapid rate but the rate gradually decreases until it becomes approximately constant during the second stage. This constant creep rate is called the minimum creep rate or steady-state creep rate since it is the slowest creep rate during the test. Evidently one can see the creep rates reach the minimum after the short primary creep at the two investigated long-term creep conditions, as shown in Fig. 2(b). In the third stage, the strain rate increases until failure occurs. Also, the increase of creep rate makes the creep rate curves much steeper. Obviously, the alloy crept at 750 °C/150 MPa has smaller minimum creep rate and longer creep rupture life than that at 700 °C/300 MPa (2768 h vs. 612 h).

3.2. Microstructural characterization

Microstructural observations were conducted on this Ni–Fe-based alloy before and after creep rupture tests to obtain the evolution in size and morphology of γ' precipitates. Fig. 3(a)-(c) display the dark field TEM images of γ' precipitates after heat treatment and two creep-rupture tests. The average size of γ' precipitates was 38 ± 3 nm after heat treatment. After creep-rupture tests at 700 °C/300 MPa and 750 °C/150 MPa, the γ' precipitates have an average size of 54 ± 5 nm and 89 ± 7 nm, respectively. It indicates that γ' precipitates coarsening occurred resulting from thermal exposure during the creep tests. While, γ' precipitates coarsening during thermal exposure may be attributed to microstructural instabilities,