Materials Science & Engineering A 651 (2016) 55–62

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

Investigation of thermal aging effects on the tensile properties of Alloy 617 by *in-situ* synchrotron wide-angle X-ray scattering

Xiang Liu [a,*], Kun Mo [b], Yinbin Miao [a,b], Kuan-Che Lan [a], Guangming Zhang [c], Wei-Ying Chen [a,b], Carolyn Tomchik [a], Rachel Seibert [d], Jeff Terry [d], James F. Stubbins [a,e]

[a] Department of Nuclear, Plasma, and Radiological Engineering, University of Illinois at Urbana-Champaign, 216 Talbot Laboratory, 104 South Wright Street, Urbana, IL 61801, USA
[b] Nuclear Engineering Division, Argonne National Laboratory, Lemont, IL 60439, USA
[c] School of Materials Science and Engineering, University of Science and Technology Beijing, Beijing 10083, China
[d] College of Science, Illinois Institute of Technology, Chicago, IL 60616, USA
[e] International Institute for Carbon Neutral Energy Research (WPI-I2CNER), Kyushu University, 744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan

A R T I C L E I N F O

Article history:
Received 10 June 2015
Received in revised form
21 October 2015
Accepted 25 October 2015
Available online 27 October 2015

Keywords:
Alloy 617
High-temperature thermal aging
Wide-angle X-ray scattering
$M_{23}C_6$ carbide

A B S T R A C T

The nickel-base Alloy 617 has been considered as the lead candidate structural material for the intermediate heat exchanger (IHX) of the Very-High-Temperature Reactor (VHTR). In order to assess the long-term performance of Alloy 617, thermal aging experiments up to 10,000 h in duration were performed at 1000 °C. Subsequently, *in-situ* synchrotron wide-angle X-ray scattering (WAXS) tensile tests were carried out at ambient temperature. $M_{23}C_6$ carbides were identified as the primary precipitates, while a smaller amount of M_6C was also observed. The aging effects were quantified in several aspects: (1) macroscopic tensile properties, (2) volume fraction of the $M_{23}C_6$ phase, (3) the lattice strain evolution of both the matrix and the $M_{23}C_6$ precipitates, and (4) the dislocation density evolution during plastic deformation. The property–microstructure relationship is described with a focus on the evolution of the $M_{23}C_6$ phase. For aging up to 3000 h, the yield strength (YS) and ultimate tensile strength (UTS) showed little variation, with average values being 454 MPa and 787 MPa, respectively. At 10,000 h, the YS and UTS reduced to 380 MPa and 720 MPa, respectively. The reduction in YS and UTS is mainly due to the coarsening of the $M_{23}C_6$ precipitates. After long term aging, the volume fraction of the $M_{23}C_6$ phase reached a plateau and its maximum internal stress was reduced, implying that under large internal stresses the carbides were more susceptible to fracture or decohesion from the matrix. Finally, the calculated dislocation densities were in good agreement with transmission electron microscopy (TEM) measurements. The square roots of the dislocation densities and the true stresses displayed typical linear behavior and no significant change was observed in the alloys in different aging conditions.

1. Introduction

The Very-High-Temperature Reactor (VHTR) is a leading candidate of the Gen-IV advanced reactors as proposed by the Next Generation Nuclear Plant (NGNP) program [1,2]. The VHTR is designed as a high-efficiency system with capabilities of providing process heat and coupling to hydrogen production facilities. The net plant efficiency of the VHTR can exceed 50% at 1000 °C, much greater than the 33% efficiency of current light water reactors. However, the high temperature environment poses challenges for reactor structural materials, especially when combined with high pressures and an aggressive atmosphere [3]. In particular, since the design lifetime of the VHTR is 60 years, high-temperature and long-term thermal-aging can induce significant degradation in the mechanical properties of the structural materials, and may pose potential challenges for long-term reactor operation.

One of the key components in the VHTR system is the intermediate heat exchanger (IHX), which is responsible for the heat transfer from the primary system to secondary systems [4,5]. The IHX is designed to function in an impure helium environment at temperatures up to 950 °C, and pressures around 7 MPa. Recently, Alloy 617, a solid-solution strengthened, nickel–chromium–cobalt–molybdenum alloy, has been selected as the structural materials for the IHX [6]. This alloy was developed in the 1970s for high-temperature applications such as gas turbines, combustion cans, ducting, and structural components for power-generating plants [7]. Numerous studies on Alloy 617 have been performed to investigate creep properties, tensile behavior at various

* Corresponding author. Fax: +1 217 333 2906.
E-mail address: xliu128@illinois.edu (X. Liu).

http://dx.doi.org/10.1016/j.msea.2015.10.098
0921-5093/