Annals of Nuclear Energy 100 (2017) 82–88

Contents lists available at ScienceDirect

Annals of Nuclear Energy

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

Tensile properties of accident-tolerant aluminum-bearing ferritic steels

Ankan Guria [1], Indrajit Charit *

Department of Chemical & Materials Engineering, University of Idaho, Moscow, ID 83844-3024, USA

ARTICLE INFO

Article history:
Received 27 September 2015
Received in revised form 8 September 2016
Accepted 9 September 2016
Available online 21 September 2016

Keywords:
Ferritic steel
Accident-tolerant fuel cladding
Kanthal APMT™ steel
Tensile test
I^2S-LWR

ABSTRACT

Tensile behavior of Kanthal APMT™ steel was studied over a temperature range from room temperature to 500 °C at three strain rates (10^{-4}, 10^{-3} and 10^{-2} s^{-1}). Yield strength, ultimate tensile strength and percentage elongation to fracture were evaluated. Serrated plastic flow was observed in a specific temperature/strain rate regime, signifying occurrence of dynamic strain aging (DSA). Characteristic features of DSA such as plateau/peak in yield and tensile strength as a function of temperature, ductility minima and negative strain rate sensitivity were also observed. The activation energy of serrated flow was found to be influenced by diffusion of interstitial impurity modified by high concentration of chromium. Microstructural examination and Vickers hardness testing were also performed on Kanthal APMT™ steel. Room temperature tensile properties of the APMT™ steel were compared with those of Goodfellow FeCralloy™ steel in the light of relevant strengthening mechanisms.

1. Introduction

Zirconium based alloys are extensively used as nuclear fuel cladding materials in light water reactors (LWR) because of their low neutron capture cross section for thermal neutrons, heat transfer properties, and other favorable characteristics (Murty and Charit, 2008). Nonetheless, the Fukushima-Daiichi incident showed that these alloys are vulnerable to various issues including the risk of explosion due to hydrogen evolution from zirconium-steam reaction under severe accident scenarios such as loss-of-coolant accident (LOCA). To address these issues, enhanced accident tolerant cladding materials with improved high temperature mechanical integrity and high temperature oxidation/corrosion resistance would be required. Advanced aluminum-bearing ferritic steels have been proposed as possible nuclear fuel cladding materials since the aluminum oxide scale provides high oxidation resistance at elevated temperatures (Zinkle et al., 2014; Terrani et al., 2014; Pint et al., 2013). APMT™ with high chromium and aluminum content is an advanced powder metallurgical, dispersion strengthened iron based alloy manufactured by Sandvik Inc. and is generally used as high temperature heating elements up to 1250 °C under a variety of environments. At elevated temperatures under oxidizing atmospheres, this advanced steel develops a dense, non-volatile, thermodynamically stable and adherent aluminum oxide (α-Al_2O_3) layer. The combination of excellent oxidation properties and high temperature strength makes the steel unique for high temperature applications (Jönsson et al., 2004).

The reported tensile data of APMT™ steel are generally available at temperatures above 800 °C. During normal operation, the cladding temperature in the Integral Inherently Safe Light Water Reactor (I^2S-LWR) core is expected to be in the 320–420 °C temperature range (Petrovic, 2014). Because of the key role played by cladding mechanical properties in the fuel rod structural integrity analysis, it is therefore important to obtain mechanical test data of these steels under this temperature range. In this study, the focus was kept on evaluating tensile properties of APMT™ steel at varying temperatures (room temperature to 500 °C) and strain rates. This is relevant because recent studies (Pint et al., 2013; Hellström et al., 2015) on this steel mostly focused on the oxidation/corrosion characteristics of this steel, not its mechanical properties.

2. Materials and methods

2.1. Material

Two Kanthal APMT™ steel rods of 12 mm diameter and 1830 mm length were procured from Sandvik, Inc. for this study. The rods were received in extruded form and the nominal chemical composition was provided by the manufacturer as Fe-21.5Cr-5.0Al-3.1Mo-0.04C-0.34Si-0.16Mn (in wt.%). Also, some minor amounts of Y, Zr and Hf are generally found to be present. The APMT™ employs a processing method bit different from the mechanically alloyed powder metallurgy alloys. Instead of mechanical alloying of powder, rapidly solidified powders made by gas atomization

* Corresponding author.
E-mail address: icharit@uidaho.edu (I. Charit).
[1] Sandvik Materials Technology, Hosur, Tamil Nadu, India 635126.

http://dx.doi.org/10.1016/j.anucene.2016.09.018
0306-4549/

are used to produce APMT™ products followed by capsule filling, hot isostatic pressing, machining of billets and hot extrusion. Exact details of the process parameters are not available due to their proprietary nature. For comparison, a FeCralloy™ steel rod (nominal composition of Fe-22Cr-5Al-0.1Y-0.1Zr along with minor amounts of C, Si, Mn etc. present) of 16 mm diameter was procured from Goodfellow Inc. and used for tensile testing in this study. However, it should be noted that precise comparison between the two materials in the current form is not possible because of the lack of adequate processing details of the two materials.

2.2. Microscopic sample preparation

Samples from axial and vertical directions of a small section of the APMT™ steel rod were sectioned and subsequently prepared following standard metallographic procedures. The samples were first hot mounted in Bakelite. After grinding and polishing, aqua regia (a mixture of hydrochloric acid and nitric acid in 3:1 ratio by volume) was used to perform etching on the metallographic samples to reveal the microstructure. The etched samples were then examined with an Olympus PMG-3 light microscope.

A thin sample disk was sectioned by using a diamond saw and mechanically thinned by grinding and polishing to about 50 μm thickness. Next, disks of 3 mm diameter were punched out of the foil using a Gatan mechanical punch. A few disks were electro-jet polished using a Fischione twin jet polisher. The electrolyte used was a mixture of methanol and nitric acid (80:20 ratio by volume) and the voltage used was about 30 V. The jetpolished specimens were examined in a JEOL 2010 J transmission electron microscope (TEM) operated at an accelerating voltage of 200 kV.

2.3. Mechanical testing

Microhardness tests were performed on the as-polished samples using a Leco LM-100 microhardness tester fitted with a Vickers indenter along two directions (axial and vertical). Tensile specimens of 25.4 mm gauge length and about 6.3 mm gauge diameter were machined keeping the specimen gauge section along the extrusion direction. The specimens were subjected to uniaxial tensile tests in an Instron 5982 tester in the temperature range of 25–500 °C and at nominal strain rates of 10^{-4}, 10^{-3} and $10^{-2}\ s^{-1}$. At first tensile tests were carried out at strain rates of 10^{-4} and $10^{-3}\ s^{-1}$ to form a preliminary map of temperature and strain rate combination where serrated flow was observed. Following that, the temperatures for carrying out tensile tests at $10^{-2}\ s^{-1}$ were determined. Since our primary objective of this work was to observe mechanical behavior of APMT steel in the temperature range of 320–420 °C and understand the serrated flow region, further tests were not conducted beyond this range for the strain rate of $10^{-2}\ s^{-1}$. During each elevated temperature test, the temperature was controlled within ±2 °C.

3. Results and discussion

3.1. Microstructural characterization

Fig. 1a and b show optical micrographs of the as-received APMT™ steel specimen along the axial and vertical directions, respectively, as observed by optical microscopy. The microstructures were taken from the center region of the mounted specimen. While the microstructure perpendicular to the axial direction was revealed as equiaxed grains only, the surface in the vertical direction exhibited a mixture of some equiaxed grains with mostly elongated grains. However, the average grain size of the microstructure was found to be 10 ± 2 μm.

Fig. 1c shows a TEM image of the APMT alloy (taken from the axial direction) microstructure of the alloy in detail. The TEM structure reveals much finer grain structure (1–3 μm) which could not be revealed in the optical micrographs. Furthermore, dislocations were found to be present in these boundaries. That is why it is thought that the grain structure is basically composed by fine subgrains. Electron-back-scatter-diffraction (EBSD) studies are currently being performed, shedding more light on this aspect. Two types of precipitates were observed. The smaller ones (40–65 nm) were found to be present in the (sub)grain interior and the larger particles (100–400 nm) were mostly on the grain boundaries. Jönsson et al. (2004) commented that in APMT™ steel the dispersed second phase particles typically consist of oxides, carbides and nitrides, which appear to be resistant to coarsening even after long-term exposure at elevated temperatures. However, in the current study no such elevated temperature experiments were performed to study the thermal stability of the dispersed particles. Nonetheless, no particle coarsening was observed in the tensile tested specimens at 300 and 500 °C as revealed by preliminary TEM observation.

3.2. Mechanical properties

Vickers microhardness testing of the APMT rod was performed both along the axial and vertical directions yielding hardness values along the axial and vertical directions to be 307 ± 7 and 316 ± 5, respectively. Thus, it can be suggested that no significant mechanical anisotropy in hardness was found to be present between the two directions of the extruded rod.

Tensile properties (yield strength, ultimate tensile strength and percentage elongation to fracture) of APMT™ steel tested under different temperatures and strain rates were evaluated. Room temperature tensile properties were evaluated at the strain rate of $10^{-3}\ s^{-1}$. Yield strength was 682 MPa, ultimate tensile strength 750 MPa and elongation to fracture 26%. Fig. 2 shows some representative engineering stress-strain curves of APMT™ steel deformed at $10^{-4}\ s^{-1}$ at different temperatures (from room temperature to 500 °C). At room temperature, the stress-strain curve was smooth. However, serrations were observed in the intermediate temperature range of 225–350 °C at $10^{-4}\ s^{-1}$ as shown in Fig. 2. At 500 °C no serration was observed.

Two specimens were tested for some temperatures and strain rates, the error being within ±10–20 MPa. Due to a large number of test conditions and limited material stock, tests could not be replicated for all the conditions. The variations of 0.2% offset yield strength (YS) and ultimate tensile strength (UTS) with temperature for different strain rates (10^{-4}, 10^{-3} and $10^{-2}\ s^{-1}$) are shown in Fig. 3a and b, respectively. As shown in those figures, the plot at $10^{-2}\ s^{-1}$ showed a plateau, that at $10^{-3}\ s^{-1}$ showed a peak and a plateau, and the curve at $10^{-4}\ s^{-1}$ showed a plateau. Fig. 3c shows the variation of elongation to fracture with temperature for different strain rates (10^{-4}, 10^{-3} and $10^{-2}\ s^{-1}$). Ductility variation is not very uniform in this steel. However, there were minima observed in the temperature range of serrated flow at all strain rates. It is important to note that all elongation to fracture values were consistently >20% even in the DSA regime. Tensile tests at higher temperatures were not carried out since the application for this steel does not call for temperatures beyond 420 °C under normal LWR operating conditions. Fig. 3d shows the variation of uniform elongation against temperature. It can be observed from the plot that within the DSA regime actually the contribution of the uniform elongation increased.

Generally, strain rate sensitivity (m) is calculated from the following equation:

$$\sigma = C\dot{\varepsilon}^{m} \quad (1)$$