Observation of serrated flow in APMTTM steel

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Abstract

Aluminum-bearing APMTTM steel is being considered as a potential fuel cladding material for a novel light water reactor design. Elevated temperature tensile tests were performed with APMTTM steel to examine the basic mechanical behavior. Serrations observed in the temperature range of 523 K to 673 K during tensile deformation of APMTTM within a range of strain rates are attributed to dynamic strain aging (DSA) with negative strain rate sensitivity. The DSA effect was due to interactions between mobile dislocations and interstitial solute atoms whose mobility was affected by the presence of high concentration of substitutional solute atoms.

Keywords: metals and alloys; Fe-Cr-Al; accident tolerant fuel cladding; serrations; dynamic strain aging; structural; light water reactor

1. Introduction

Traditionally, zirconium based alloys are used as fuel cladding materials in light water reactors (LWRs). Exothermic reaction with steam under accident conditions may lead to production of hydrogen with possibility of catastrophic consequences. Hence, the I²S-LWR reactor project [1] is considering an aluminum-rich (about 5 wt.%) ferritic steel as an alternative accident-tolerant fuel cladding material to zirconium-based alloys. This type of material creates an aluminum-based oxide scale protecting the alloy at elevated temperatures. Kanthal APMTTM is advanced ferritic steel with a composition of Fe-21.5Cr-5.0Al-3.1Mo-0.04C-0.34Si-0.16Mn (wt.%) steel, produced via a powder metallurgy process by Sandvik Inc., and is generally used for making high temperature furnace heating elements. With excellent high-temperature corrosion/oxidation resistance, this steel has the potential of being used as a fuel cladding material for nuclear applications.

In the present work, a preliminary investigation was performed on the influence of strain rate and temperature on serrated flow observed during tensile deformation of APMTTM alloy. While there are high temperature tensile data available above 800°C for this alloy in the open literature [2], the tensile properties of this alloy in the low temperature range are not

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1 available. Given that the normal LWR core outlet temperature is around 593 K to 693 K, it is
2 important to study the alloy in this temperature range. However, the experimental campaign
3 designed for the current work included a broader temperature range (298 K to 773 K) to gain
4 further scientific insights into the relevant phenomena.
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6 Earlier, ferritic-martensitic steels such as Grade 9 [3,4-7] and Grade 91 [8-13] 9Cr–
7 1Mo steel, P9 and P91 [14,15] and P92 [16] have been reported to exhibit dynamic strain
8 aging (DSA) over the temperature range of 498 K to 693 K. Occurrence of DSA in these
9 steels has been manifested by serrated plastic flow, plateau in yield and tensile strength,
10 negative strain rate sensitivity and ductility minima [8-12]. DSA in the conventional 9Cr–
11 1Mo steel has been attributed to interactions of dislocations with carbon atoms [3,4-6], and
12 with nitrogen atoms in the modified 9Cr–1Mo steel [8,9,12]. On the other hand, Keller et al.
13 [11] suggested that DSA occurs due to carbo-nitrides. Serrations due to DSA have also been
14 characterized by internal friction in several materials like austenitic stainless steel [17], nickel
15 based superalloy [18], and zirconium–hydrogen alloy [19].
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17 Based on the nature of serrations, A-, B-, C- and D-type of serrations have been
18 reported in earlier experiments with ferritic steels [3-13]. Type A serrations exhibit repeated
19 initiation and continuous propagation of deformation bands along the specimen gage length.
20 Sleeswyk [20] and McCormick [21] in their diffusion-controlled models of DSA attributed
21 the occurrence of A-type serrations to diffusion of solute atoms to freely gliding dislocations.
22 Sharp rise in load occurs when the solute locks dislocations, and the load drops when
23 dislocations unlock from the solute atmosphere. Following A-type serrations, repeated
24 locking and unlocking of dislocations due to highly mobile solutes lead to small B-type
25 serrations about the mean level of loads in load-elongation curves. Type C serrations are
26 oscillations of the load-elongation curve below the mean level of load. Type D serrations
27 occur as plateaus due to band propagation similar to Luders band with not much work
28 hardening or strain gradient ahead of the moving band front [22, 23].
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30 Generally, DSA has been found to be detrimental to tensile ductility, low cycle
31 fatigue (LCF) life and creep resistance of structural components which are causes of concern
32 for structural applications [24]. Hence, the role of DSA occurring in a LWR-specific service
33 temperature range (553–693 K) on the tensile behavior of APMTTM alloy is addressed in this
34 study.
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36 2. Methods

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1 An APMTTM steel rod of 12 mm diameter and 1830 mm length was procured from
2 Sandvik for this study. Round tensile specimens of 25.4 mm gauge length and 6 mm gauge
3 diameter were subjected to tensile tests in the temperature range of 298 – 773 K in air using
4 nominal strain rates of 10^{-4} , 3×10^{-4} , 10^{-3} , 3×10^{-3} , and 10^{-2} s^{-1} . The tensile specimens were
5 allowed to dwell at the test temperature for 30 min to reach temperature stabilization
6 throughout the specimens before starting elevated temperature tests. Stress–strain curves
7 were established from the load extension data and 0.2% offset yield stress (YS), ultimate
8 tensile stress (UTS) and ductility parameters e.g. elongation to fracture and reduction in area
9 were determined. Variation of these properties as a function of temperature was plotted.
10 Fracture surfaces of the tensile tested specimens were examined by field emission scanning
11 electron microscope (Zeiss Supra 35 VP).
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21 3. Results and Discussion

22 The steel exhibited serrated flow in the temperature range of 523 K to 673 K. Figure
23 1a shows the variation in serration types at different strain rates at a temperature of 573 K
24 while Figure 1b shows the different types of serrations at different temperatures for a strain
25 rate of 10^{-3} s^{-1} . The curves were shifted from their respective original positions to avoid
26 overlapping and make the serrations distinct. Lower strain rates like $3 \times 10^{-4} \text{ s}^{-1}$ and 10^{-4} s^{-1}
27 exhibited the dominance of A or A+C serrations, whereas at higher strain rates B and D types
28 of serrations appeared. The lowermost curve in Figure 1a shows a stress-strain curve obtained
29 from strain rate jump test. With increase in strain rate from $3 \times 10^{-4} \text{ s}^{-1}$ to 10^{-2} s^{-1} , stress values
30 decrease which is against the normal behavior.
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39 Unlike other research works done on serrations in low carbon steels exhibiting
40 appreciable critical strain for the onset of serrations, in APMTTM alloy such serrated flow
41 started almost near the onset of plastic deformation. Interestingly, serrations were observed
42 almost throughout the plastic flow at 573 K for all strain rates. With increase in plastic
43 deformation, denser serrations were observed at this temperature. Relevant activation energy
44 values were calculated according to a method used by Jenkins and Smith [25]. The activation
45 energy for the onset of serrations was found to be ~142 kJ/mol and that for their
46 disappearance ~212 kJ/mol. Such activation energy suggests that the onset of serrations was
47 likely linked to the migration of interstitial solutes such as carbon whose mobility was
48 substantially affected by the substitutional solutes (such as Cr). On the other hand, the
49 activation energy values of Cr diffusion in Cr-enriched ferritic steels have been reported to be
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216 kJ/mol (in Fe-19Cr) and 202 kJ/mol (in Fe-25Cr) [26, 27], which are similar to the activation energy (~ 212 kJ/mol) found for disappearance of serrations.

Double logarithmic plots of true stress versus strain rate at 573 K for various true plastic strains (ϵ_p) are shown in Figure 2a. The negative strain rate sensitivity, which is clearly evident from the Regime-2 in the figure, is a manifestation of DSA. At higher strain rates, the true stress increases again, as the effect of DSA diminishes. Figure 2b exhibits the variation of 0.2% offset YS and UTS with temperature. In the temperature range of 573 K to 673 K, there is positive variation of YS and UTS values with temperature, which is also considered a manifestation of DSA [4, 6, 12, 28, 29, 30].

The three distinct regimes observed in Fig. 2a can be explained by corresponding deformation mechanisms [26]. Easy deformation due to free glide and cross slip activity at lower levels of strain rates cause the decrease in true stress in Regime-1 [16]. Regime-2 exhibits abrupt decrease in true stress with strain rate i.e. negative strain rate sensitivity, which is a characteristic manifestation of DSA. Regime-3 shows the increase of true stress with increase in strain rate due to increasing difficulty in easy glide of dislocations. At a particular temperature in the DSA region (573 K), propensity towards occurrence of DSA increases with decrease in true plastic strain. The variation in elongation to fracture and reduction in area with temperature are shown in Figure 3. Though ductility falls appreciably at the onset of DSA temperature regime, it shows marginal decrease/plateau in the temperature range of DSA. While the variation of elongation to fracture with temperature exhibits a marginal decrease, reduction in area shows a plateau. Unlike most other ferritic steels, the significant appearance of minima in the ductility-temperature variation curve in the DSA temperature range is not observed.

The increase in strength values and decrease in ductility in the temperature range of 573 to 673 K noted for APMTTM steel (Figures 2b and 3) suggest the dominance of DSA. On the other hand, decrease in strength and increase in ductility beyond 673 K exhibits the dominance of recovery processes [31].

4. Conclusions

The APMTTM steel exhibited serrated flow during tensile deformation within a temperature range of 523 K to 673 K at all strain rates. Negative strain rate sensitivity predicts that serrated flow is due to DSA in this temperature range caused by interactions between mobile dislocations and interstitial solutes whose mobility is affected by high

concentration of substitutional solutes. Further analysis is needed to fully assess the application of APMTTM steel as a fuel cladding material for the I²S-LWR concept.

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List of Figure Captions

Figure 1. Variation of engineering stress with engineering strain at (a) different strain rates at 573 K and (b) different temperatures at 10^{-3} s^{-1}

Figure 2. (a) Variation of true stress with strain rate at different true plastic strains at 573 K (b) Variation of yield stress and ultimate tensile stress with temperature at 10^{-3} s^{-1}

Figure 3. The variation of percentage elongation to fracture and reduction in area as a function of test temperature

Figure 1a

Figure 1b

Figure 2a

Figure 2b

Figure 3