Report on Thermal Aging Effects on Tensile Properties of Advanced Austenitic Steels

Nuclear Engineering Division

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September 2011

ABSTRACT

This report provides an update on the evaluation of thermal-aging induced degradation of tensile properties of advanced HT-UPS austenitic stainless steels. The report is the second deliverable (level 3) in FY11 (M3A11AN04030103), under the Work Package A-11AN040301, “**Advanced Alloy Testing**” performed by Argonne National Laboratory, as part of Advanced Structural Materials Program for the Advanced Reactor Concepts. This work package supports the advanced structural materials development by providing tensile data on aged alloys and a mechanistic model, validated by experiments, with a predictive capability on long-term performance.

The scope of work is to evaluate the effect of thermal aging on the tensile properties of advanced alloys such as ferritic-martensitic steels, mod.9Cr-1Mo (G91), G92, and advanced austenitic stainless steel, HT-UPS. The aging experiments have been conducted over a temperature of 550-750°C for various time periods to simulate the microstructural changes in the alloys. In addition, a mechanistic model based on thermodynamics and kinetics has been used to address the changes in microstructure of the alloys as a function of time and temperature, which is developed in the companion work package at ANL. The focus of this project is advanced alloy testing and understanding the effects of long-term thermal aging on the tensile properties.

The first deliverable of FY11 reported the tensile testing results of thermally-aged G92 in the normalized and tempered condition (H1 G92), G92 in the cold-rolled condition (H2 G92), and reference alloy, G91 ferritic-martensitic steels. This report summarizes the tensile data of thermally aged HT-UPS austenitic stainless steel. Two heats of HT-UPS have been investigated, i.e., solution-annealed HT-UPS (SA HT-UPS) and hot-rolled HT-UPS (HR HT-UPS). Tensile data have been obtained for SA HT-UPS thermally-aged for up to 18031 h at 550°C and for up to 17595 h at 650°C, as well as for HR HT-UPS thermally aged for up to 6909 h at 550°C, 4293 h at 600°C, and 5407 h at 650°C.

Major findings are: (1) the solution-annealed HT-UPS showed continued, moderate increase in strength and decrease in ductility with increasing aging time up to 18034 h at 550°C. Thermal aging at 650°C increased the yield stress and decreased the ultimate tensile strength and drastically reduced the ductility in the SA HT-UPS. For the HR HT-UPS, thermal aging at 550°C for up to 6909 h showed little influence on its tensile behavior. Thermal aging at 600°C for 4293 h increased the strength and decreased the ductility. The 650°C-thermally-aged HR HT-UPS specimens showed very different strengthening, strain hardening, and flow localization behavior. Thermal aging at 650°C increased the yield stress but decreased the ultimate tensile stress for the HR HT-UPS. (2) Dynamic strain aging (DSA) was observed in both the solution-annealed HT-UPS and the hot-rolled HT-UPS at temperatures between 550-650°C at a strain rate of 0.001 s⁻¹. Extensive precipitation in the matrix after thermal aging at 600 and 650°C significantly reduced serrated plastic flow observed in the stress-strain curves, i.e. less effect of DSA. Because the DSA phenomenon can have significant influence on tensile, creep strength, and fatigue resistance, and the DSA effects in HT-UPS steels were observed in the

temperature range of interest to the SFR applications, the DSA phenomenon in the HT-UPS steels deserves a more comprehensive investigation.

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1 Introduction

Advanced materials are a key element to the development of advanced nuclear energy systems. High-performance structural materials allow compact and simple design of reactor structure and have the potential to reduce the construction and operational costs for next-generation nuclear reactors. Several advanced alloys have been selected for further development in support of sodium-cooled fast reactors (SFRs) [Busby et al 2008]. R&D has focused on advanced ferritic-martensitic steels, G92 and G92 with special thermal-mechanical treatment, and advanced austenitic stainless steels, High-Temperature Ultrafine Precipitate-Strengthened (HT-UPS) steel.

G92 offers the best high temperature strength among commercially available ferritic-martensitic steels. G92 is a variant of mod.9Cr-1Mo (G91) ferritic-martensitic steel. G91 steel was developed in 1980s for applications in liquid metal fast breeder reactors. It has improved high temperature strength and creep properties compared to Sandvik HT-9, a ferritic-martensitic steel traditionally considered for liquid metal fast reactors [Klueh and Harries 2001]. The high temperature strength and creep resistance of G92 and G91 rely on tempered martensitic microstructure stabilized by $M_{23}C_6$ carbides, a fine distribution of vanadium/niobium carbonitride (MX) precipitates, and solution strengthening by Mo (and/or W) [Klueh and Harries 2001].

The HT-UPS is a 14Cr-16Ni austenitic stainless steel containing nanometer-sized Ti+Nb+V carbide precipitates and possesses increased creep resistance and irradiation tolerance over traditional 316 SS [Busby et al 2008]. Because advanced materials heavily rely on fine second-phase precipitate particles for improved high temperature strength, creation and maintenance of the precise microstructure during fabrication and heat treatment and during service is the key to achieve their superior properties. The properties of advanced materials generally degrade with time, when exposed to high temperatures. Significant microstructural changes, during prolonged thermal exposure, can lead to dramatically different responses to service environments. Research has shown that long-term exposure of G92 and G91 to high temperatures can result in significant microstructural changes, leading to degradation in high temperature performance as well as embrittlement at low temperatures [Klueh and Harries 2001]. Microstructural stability and mechanical property degradation during long-term aging is also a major concern in the nuclear structural applications of these advanced alloys. It is critically important to understand the fundamental relationship between microstructures and mechanical behavior such that aging-induced degradation on mechanical performance and material failure can be reliably predicted in structures and components.

The objective of this project is to evaluate the effect of thermal aging on the tensile properties of advanced alloys including G92 ferritic-martensitic steel and G92 with special thermal-mechanical treatments, and advanced austenitic stainless steel, HT-UPS. The aging experiments have been conducted over a temperature range of 550-750°C for various time periods to simulate the microstructural changes in the alloys as a function of time and temperature. A companion project is being conducted at ANL to develop a mechanistic model based on thermodynamics and kinetics to address the changes in microstructure of the alloys as a function of aging time and temperature. The focus of this project is on testing of advanced alloys with emphasis on

understanding the effects of long-term thermal aging on the tensile properties. The first deliverable of FY11 [Li et al 2011] reported the tensile testing results of thermally aged G92 in the normalized and tempered condition (H1 G92), G92 in the cold-rolled condition (H2 G92), and reference alloy, G91 ferritic-martensitic steels. This report summarizes the tensile data of thermally aged HT-UPS austenitic stainless steels. Two heats of HT-UPS have been investigated, i.e., solution-annealed HT-UPS (SA HT-UPS), and hot-rolled HT-UPS (HR HT-UPS). Tensile data have been obtained for SA HT-UPS thermally-aged for up to 18031 h at 550°C and for up to 17595 h at 650°C, as well as for HR HT-UPS thermally aged for up to 6909 h at 550°C, 4293 h at 600°C, and 5407 h at 650°C.

2 Experimental Procedure

2.1 Materials and Specimens

Two heats of HT-UPS were examined. Heat AX-6 was in sheet form with a thickness of 2 mm. It was annealed at 1200°C for 1 h (referred to SA HT-UPS). The second heat of HT-UPS was in plate form with a thickness of 0.75 in. The final process was hot rolling at 1200°C followed by air cooling (referred to HR HT-UPS). Both heats were provided by the Oak Ridge National Laboratory (ORNL). The chemical analysis for SA HT-UPS was carried out by Bodycote Materials Testing. The chemical compositions of HR HT-UPS were provided by ORNL. The chemical compositions are given in Table 1. The heat treatment conditions are summarized in Table 2.

Two types of sheet-type tensile specimens were used in the thermal aging experiments and follow-on tensile tests, one type with a short grip section for SA HT-UPS, shown in Fig. 1(a), and another with an extended grip section for HR HT-UPS shown in Fig. 1(b), respectively. The extended grip sections of the exposed tensile specimen were cut from both ends for use in microstructural characterization. The tensile specimens were electrical-discharge-machined with the gage parallel to the rolling direction. The tensile specimens have gage dimensions of $7.62 \times 1.52 \times 0.75$ mm.

2.2 Thermal Aging Experiments and Post-Aging Examinations

Thermal aging experiments were performed at temperatures between 550 and 650°C for various exposure times to examine microstructural evolution during long-term thermal aging and its effects on tensile properties. Each tensile specimen was wrapped in Ta foil, and encapsulated in a vacuum quartz tube. Encapsulated specimens were loaded in an air furnace heated to the target temperature for an extended period.

Thermally aged specimens were tested under uniaxial tension to examine the effects of aging on tensile properties. Tensile tests were performed in a MTS screw-driven machine at either at room temperature or at the aging temperature in air at a nominal strain rate, 0.001 s^{-1} . The tensile specimen was heated in a three-zone air furnace. The applied load was recorded by a load cell and the specimen displacement was recorded using a linear variable differential transformer (LVDT) attached to the load train. The engineering tensile properties were determined from an analysis of the load versus displacement data files. Figure 4 shows the setup for high temperature tensile testing.

The microstructure of as-received and thermally aged specimens was characterized by optical microscopy, high-resolution scanning electron microscopy (HR-SEM), transmission electron microscopy (TEM), and synchrotron X-ray diffraction. The grain structure of the alloys was revealed by optical microscopy. Metallographic specimens were further examined by high resolution scanning electron microscopy to characterize carbide precipitates, using both secondary electron and backscattered electron imaging (SE and BSE) on a field emission gun (FEG) Hitachi S-4700-II microscope. Transmission Electron Microscopy was used to examine

detailed microstructure of dislocations, subgrains, and second-phase particles. Phases and precipitate microstructure of as-received and thermally aged specimens were characterized by high-energy synchrotron X-ray diffraction (HE-XRD) and high-resolution X-ray diffraction (HR-XRD). The results on microstructure evolution during thermal aging are reported in a companion project [Li et al. 2011].

Table 1. Chemical composition (in wt%)

Alloy	Fe	C	Mn	P	S	Si	Ni	Cr	Mo	B	Ti	Nb	V	N	W
SA HT-UPS	Bal	0.06	2.13	0.038	0.009	0.10	16.86	14.63	2.66	0.0044	0.29	0.11	0.53	-	-
HR HT-UPS	Bal	0.058	2.08	0.048	6 ppm	0.28	16.06	14.54	2.33	0.007	0.15	0.15	0.53	0.028	

Table 2. Heat treatment conditions

Alloy	Heat treatment
SA HT-UPS	Annealed at 1200°C for 1 h
HR HT-UPS	Hot-rolled at 1200°C

Figure 1. Schematic drawing of sheet-type tensile specimens (a) short-grip tensile specimens for SA HT-UPS steel and (b) extended-grip tensile specimens for HR HT-UPS.

Figure 2. Experimental setup for high temperature tensile testing.

3 Experimental Results

3.1 Effects of Thermal Aging on Tensile Behavior

As the baseline property, the as-received SA HT-UPS was tested at different temperatures, and its engineering stress-strain curves are shown in Fig. 3. A strong temperature dependence of tensile behavior is evident for SA HT-UPS steel. Tensile strength increases and ductility decreases with increasing temperature. The SA HT-UPS steel exhibits pronounced strain hardening at all the test temperatures and shows limited localized flow after the maximum load is reached. It was also observed that serrations in the stress-strain curves appeared at a certain temperature range, a phenomenon so-called “dynamic strain aging” (DSA) often observed in 316 SS [Karlsen et al. 2009, Hong and Lee 2005]. As the DSA can have a significant influence on tensile, fatigue, and creep-fatigue behavior of a material, the DSA in HT-UPS steels and the effect of thermal aging on DSA will be discussed in the following section.

Figure 4 shows the stress-strain curves for SA HT-UPS steel in the solution-annealed (as-received) condition and after thermal aging for 7045 h and 18034 h at 550°C, tensile tested at the aging temperature of 550°C. Note that the material’s yield and ultimate tensile strength continued to increase and ductility continued to decrease with increasing aging time at 550°C. The strain hardening and flow localization behavior are almost similar for the as-received and thermally aged specimens. Serrations (i.e. DSA effect) were observed in all three stress-strain curves.

Figure 5 shows the stress-strain curves for SA HT-UPS steel in the solution-annealed (as-received) condition and after thermal aging for 5000 h and 17595 h at 650°C, tensile tested at the aging temperature of 650°C. In contrast to the data of the 550°C-aged specimens, thermal aging at 650°C significantly increased the yield strength, but reduced the ultimate tensile strength of SA HT-UPS. Ductility of the SA HT-UPS steel decreased drastically with increasing aging temperature. The total elongation of the 650°C-17595 h aged specimen is 16%, relative to 38% total elongation of the as-received specimen. Serrations (i.e. DSA effect) in the stress-strain curves nearly diminished after thermal aging at 650°C.

Figure 6 shows the stress-strain curves for the hot-rolled HT-UPS (HR HT-UPS) tested at temperatures between 20-650°C as the baseline data to compare with thermally aged specimens. The temperature dependence of tensile behavior for HR HT-UPS steel is similar to that for SA HT-UPS. Tensile strength increased and ductility decreased with increasing temperature. The steel exhibits pronounced strain hardening at all test temperatures, and limited localized flow. The DSA effect was observed at 550-650°C. The HR HT-UPS shows a relatively higher strength than the SA HT-UPS at all test temperatures.

Figure 7 shows the stress-strain curves for HR HT-UPS steel in the as-received condition and after thermal aging for 6909 h at 550°C, tensile tested at the aging temperature of 550°C. Thermal aging at 550°C shows no influence on the strength but reduced the ductility of HR HT-UPS. The as-received and thermally aged specimens showed nearly identical strain

hardening and flow localization behavior. Serrations (i.e. DSA effect) were observed in both stress-strain curves.

Figure 8 shows the stress-strain curves for HR HT-UPS steel in the as-received condition and after thermal aging for 4293 h at 600°C, tensile tested at the aging temperature of 600°C. The yield stress and ultimate tensile strength increased, and the ductility decreased after thermal aging at 600°C in HR HT-UPS. No significant changes were noted in strain hardening and flow localization behavior. Serrations in the stress-strain curves became more moderate (or different type of DSA) after thermal aging.

Figure 9 shows the stress-strain curves for HR HT-UPS steel in the as-received condition and after thermal aging for 1200 h and 5407 h at 650°C, tensile tested at the aging temperature of 650°C. Thermal aging at 650°C significantly increased the yield stress, but reduced the ultimate tensile strength. The strain hardening and flow localization behavior was also quite different in the thermally aged specimen compared to the as-received specimen. It is apparent that different strengthening mechanism was operative in the thermally aged specimens from that in the as-received specimen. The ductility of the thermally aged specimen was reduced after 1200 h exposure and increased and recovered to nearly the same total elongation as in the as-received condition. Serrations in the stress-strain curves became less pronounced after thermal aging at 650°C.

A summary of tensile properties, yield stress (YS), ultimate tensile strength (UTS), uniform elongation (UE), total elongation (TE), and hardness, for thermally aged specimens of SA HT-UPS and HR HT-UPS steels is given in Table 3.

Figure 3. Stress-strain curves for solution-annealed HT-UPS (SA HT-UPS) steel tested at temperatures between 20 and 750°C.

Figure 4. Stress-strain curves for solution-annealed HT-UPS (SA HT-UPS) steel in as-received condition and after thermal aging at 550°C for up to 18034 h.

Figure 5. Stress-strain curves for solution-annealed HT-UPS (SA HT-UPS) steel in as-received condition and after thermal aging at 650°C for up to 17595 h.

Figure 6. Stress-strain curves for hot-rolled HT-UPS (HR HT-UPS) steel tested at temperatures between 20 and 650°C.

Figure 7. Stress-strain curves for hot-rolled HT-UPS (HR HT-UPS) steel in as-received condition and after thermal aging at 550°C for 6909 h.

Figure 8. Stress-strain curves for hot-rolled HT-UPS (HR HT-UPS) steel in as-received condition and after thermal aging at 600°C for 4293 h.

Figure 9. Stress-strain curves for hot-rolled HT-UPS (HR HT-UPS) steel in as-received condition and after thermal aging at 650°C for up to 5407 h.

Table 3. Effects of thermal aging on tensile properties of HT-UPS steels.

Alloy	Condition	Test T (°C)	Strain Rate (s ⁻¹)	YS (MPa)	UTS (MPa)	UE (%)	TE (%)
SA HTUPS	As received	20	0.001	206	519	54	61
SA HTUPS	As received	550	0.001	68	382	47	51
SA HTUPS	550°C 7045 h	550	0.001	121	411	39	43
SA HTUPS	550°C 18031 h	550	0.001	149	414	32.5	35.5
SA HTUPS	As received	650	0.001	126	380	34	38
SA HTUPS	650°C 5000 h	650	0.001	196	344	22	28
SA HTUPS	650°C 17595 h	650	0.001	206	322	12	16
SA HTUPS	As received	750	0.001	124	286	27	42
HR HTUPS	As received	20	0.001	221	562	51	57
HR HTUPS	As received	550	0.001	118	440	47	51
HR HTUPS	550°C 6909 h	550	0.001	147	435	40	45
HR HTUPS	As received	600	0.001	133	415	40	46
HR HTUPS	600°C 4293 h	600	0.001	167	433	33	37
HR HTUPS	As receive	650	0.001	129	394	40	46
HR HTUPS	650°C 1200 h	650	0.001	167	350	25	35
HR HTUPS	650°C 5407 h	650	0.001	168	355	25	47

3.2 Effects of Thermal Aging on Dynamic Strain Aging Behavior

Dynamic strain aging (DSA) is often observed in austenitic stainless steels in the temperature range of 200-800°C [Almeida and Monteiro 1976, Jenkins and Smith 1969]. It is manifested by serrated plastic flow in the stress-strain curve under uniaxial tensile loading. DSA has also been observed under creep and fatigue loading [Rodriguez 1984, Srinivasan et al. 1991, 1999, Hong and Lee 2004, 2005]. DSA is caused by interactions between mobile dislocations and diffusing solute atoms, and its occurrence depends on both temperature and strain rate. DSA promotes planar slip due to interactions between mobile dislocations and solute atmospheres. Deformation under the DSA condition can have significant impact on mechanical properties such as strength and ductility. DSA-induced deformation inhomogeneity can enhance crack initiation and also enhance crack propagation rate [Hong and Lee 2004, 2005]. A steep reduction in fatigue resistance of Type 316L stainless steel has been observed in the DSA regime [Hong and Lee 2005]. The so-called “DSA pre-treatment” was found to be beneficial to both tensile strength and creep strength for 18-8 type austenitic stainless steels [Peng et al. 2004].

Different types of serrated plastic flow can occur under different experimental conditions. Rodriguez [1984] summarized five types of DSA serrations, termed A, B, C, D, and E shown in Fig. 10. Types A, B, and C are the most commonly observed. As shown in the previous section, DSA was observed in both solution-annealed HT-UPS and hot-rolled HT-UPS steels. Serrated plastic flow is pronounced during strain hardening stage under tensile loading at temperatures between 550-650°C at a strain rate of 0.001 s^{-1} . When tested at 550°C, HT-UPS steels showed approximately “Type A” DSA behavior, while when tested at 600 and 650°C, transitioned to “Type (A+B)” DSA behavior.

Thermal aging can significantly alter the DSA effect in HT-UPS. As shown in Fig. 11 which compares a portion of the stress-strain curves for SA HT-UPS in the as-received condition and thermally-aged for 5000 h at 650°C and tensile tested at 650°C at a strain rate of 0.001 s^{-1} , serrated plastic flow diminished in the aged specimen. Figure 12 shows a portion of the stress-strain curves for HR HT-UPS in the as-received condition and thermally-aged for 6293 h at 600°C and tensile tested at 650°C at a strain rate of 0.001 s^{-1} . The “Type A + B” serrations are shown in the as-received specimen, while somewhat “Type A” DSA behavior is shown in the thermally aged specimen.

Figure 10. Types of DSA serrations [Rodriguez 1984].

Figure 11. Magnified view of serrations in the stress-strain curves for SA HT-UPS in the as-received condition and thermally aged at 650°C for 5000 h and tensile tested at 650°C at a strain rate of 0.001 s⁻¹.

Figure 12. Magnified view of serrations in the stress-strain curves for HR HT-UPS in the as-received condition and thermally-aged at 600°C for 6293 h and tensile tested at 600°C at a strain rate of 0.001 s⁻¹.

3.3 Relationship between Microstructural Changes and Tensile Behavior

The effects of thermal aging on tensile behavior can be best understood when the thermal aging-induced microstructural changes can be linked directly with the tensile properties of the same specimen. In a companion project, detailed microstructural analysis and modeling of microstructural evolution during thermal aging is being conducted, and the recent results can be found in the report [Li et al. 2011]. As shown in Fig. 1, the tensile specimens being tested have extended grips which allow microstructural and mechanical characterization to be performed on the same piece of thermally aged specimen. The advantage is obvious: tensile property, thermally-aged and non-deformed microstructure, and thermally-aged and deformed microstructure can be obtained at the same time, which provide critical information to develop an insight into the deformation and fracture mechanisms, and ultimately lead to a mechanistic model for prediction of lifetime in real engineering environments.

Figure 13 shows the TEM images of the SA HT-UPS specimens (a) in as-received condition, (b) after aging at 550°C for 18031 h, and (c) after aging at 650°C for 7595 h, respectively. The solution-annealed specimen is nearly free of dislocations. Only large inclusions were observed in the austenite matrix. Due to the high concentration of solute atoms in the matrix, the SA HT-UPS showed strong serrated plastic flow and DSA effect when tested at 550-650°C at a strain rate of 0.001 s^{-1} . After aging for 18031 h at 550°C, only grain boundary precipitates were observed, as shown in Fig. 13(b). There was no significant change in DSA behavior under this thermal aging condition. The specimen aged for 7595 h at 650°C, however, shows extensive precipitation of “needle-shaped” precipitates in the austenite matrix (Fig. 13(c)). These “needle-shaped” precipitates were reported to be phosphides (MP) in the literature [Maziasz 1989, Lee et al. 1984, 2000, Swinderman et al. 1987, 1990]. Grain boundaries are heavily decorated by precipitates after aging for 7595 h at 650°C. The precipitation of fine phosphides in the matrix can explain the change in strain hardening behavior in the thermally aged specimen, which showed different strengthening mechanism from that in the solution-annealed specimen. Because of extensive precipitation and removal of solute atoms from the matrix, the serrated flow in the stress-strain curves became less evident. The significant reduction in ductility is likely associated with heavy precipitation at grain boundaries.

Figure 14 shows the HR HT-UPS specimens (a) in as-received condition, (b) after aging at 600°C for 4293 h, and (c) after aging at 650°C for 5407 h, respectively. Low density of dislocation segments and large size inclusions were observed in the austenite matrix in the as-received hot-rolled specimen. Significant precipitates were observed after aging for 4293 h at 600°C, as shown in Fig. 14(b). “Needle-shaped” precipitates were observed and considerable bending of the foil occurred in the precipitation region. Round-shaped precipitates (possibly MC carbides) surrounded by dislocation tangles were also observed in the matrix. Grain boundaries were heavily decorated by second-phase particles as well. Figure 14(c) shows the microstructure of HR HT-UPS thermally aged for 5407 h at 650°C. Both well-lined “needle-shaped” precipitates and blocky precipitates were observed in the matrix, and both types of precipitates are surrounded by dislocations. Reduction in the number of interstitial atoms in the matrix due to thermal aging induced precipitation changes the DSA behavior and

strengthening mechanisms in the thermally aged specimens. Grain boundary precipitation and segregation could contribute to the changes in ductility.

(a) As-received

(b) Thermally-aged at 550°C for 18031 h

(c) Thermally-aged at 650°C for 17595 h

Figure 13. TEM images showing microstructures of SA HT-UPS steel (a) as-received condition, (b) after aging at 550°C for 18031 h, and (c) after aging at 650°C for 7595 h.

(a) As-received

(b) Thermally-aged at 600°C for 4293 h

(c) Aged at 650°C for 5407 h

Figure 14. TEM images showing microstructures of HR HT-UPS steel (a) as received condition, (b) after aging at 600°C for 4293 h, and (c) after aging at 650°C for 5407 h.

4 Summary

This report provides an update on the evaluation of thermal-aging induced degradation in tensile properties of advanced HT-UPS austenitic stainless steels. The first deliverable of FY11 reported the tensile testing results of thermally-aged G92 in the normalized and tempered condition (H1 G92), G92 in the cold-rolled condition (H2 G92), and reference alloy, G91 ferritic-martensitic steels. This report summarizes the tensile data of thermally aged HT-UPS austenitic stainless steels with two heats, i.e., solution-annealed HT-UPS (SA HT-UPS), and hot-rolled HT-UPS (HR HT-UPS). Tensile data were obtained for SA-HTP aged for up to 18031 h at 550°C and for up to 17595 h at 650°C, as well as for HR HT-UPS aged for up to 6909 h at 550°C, 4293 h at 600°C, and 5407 h at 650°C.

Major findings are:

(1) The solution-annealed HT-UPS showed continued, moderate increase in strength and decrease in ductility with increasing aging time up to 18034 h at 550°C. Thermal aging at 650°C increased the yield stress and decreased the ultimate tensile strength and drastically reduced the ductility in the SA HT-UPS. For the HR HT-UPS, thermal aging at 550°C for up to 6909 h showed little influence on its tensile behavior. Thermal aging at 600°C for 4293 h increased the strength and decreased the ductility. The 650°C-thermally-aged HR HT-UPS specimens showed very different strengthening, strain hardening, and flow localization behavior. Thermal aging at 650°C increased the yield stress but decreased the ultimate tensile stress for the HR HT-UPS.

(2) Dynamic strain aging (DSA) was observed in both the solution-annealed HT-UPS and the hot-rolled HT-UPS at temperatures between 550-650°C at a strain rate of 0.001 s^{-1} . Extensive precipitation in the matrix after aging at 600 and 650°C significantly reduced serrated plastic flow observed in the stress-strain curves, i.e. less effect of DSA. Because the DSA phenomenon can have significant influence on tensile, creep strength, and fatigue resistance, and the DSA effects in HT-UPS steels were observed in the temperature range of interest to the SFR applications, the DSA phenomenon in the HT-UPS steels deserves a more comprehensive investigation.

Acknowledgement

Materials were provided by the Oak Ridge National Laboratory. Work was supported by the U.S. Department of Energy, Office of Nuclear Energy under Contract DE-AC02-06CH11357.

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