FY 2017-Influence of Sodium Environment on the Tensile Properties of Advanced Alloys

Nuclear Engineering Division

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ABSTRACT

This report provides an update on the understanding of the effects of sodium exposures on tensile properties of advanced alloy 709 in support of the design and operation of structural components in sodium-cooled fast reactors (SFRs). The report is a Level 3 deliverable in FY17 (M3AT-17AN1602093), under the Work Package AT-17AN160209, “Sodium Compatibility” performed by Argonne National Laboratory (ANL), as part of Advanced Reactor Technologies Program.

Three laboratory-size heats of Alloy 709 austenitic steel were investigated in liquid sodium environments at 550-650°C to understand its corrosion behaviour, microstructural evolution, and tensile properties. In addition, a commercial scale heat has been produced and hot-rolled into plates.

- All the heats of Alloy 709 exhibited negligible weight loss at the exposure temperature of 650°C, and all the alloys showed similar weight loss behavior.
- The hardness profiles of sodium exposed Alloy 709 specimens showed little variation after ≈5,000 h sodium exposure and were comparable to those obtained with thermally aged specimens. However, the hardness values for Alloy 709 were significantly higher than for Type 316 stainless steel after sodium exposure indicating the inherent higher strength for Alloy 709 and its retention of the strength even after sodium exposure.
- Microstructural analysis of the ≈5000 h sodium-exposed Alloy 709 specimens showed stable microstructures and the fine precipitate morphology, indicating limited mass transport between the alloy and sodium at 650°C.
- Currently, long term exposures of specimens are being conducted at 600 and 550°C to supplement the data developed after sodium exposure at 650°C.
- A commercial-scale heat of Alloy 709 has been procured and detailed analysis of the material exhibit tensile properties that exceed the minimum values specified in the ASME Code Case for commercial heat of NF709. The material from this heat will be exposed to sodium environment to validate its performance.
- Based on the sodium compatibility studies, in terms of tensile properties, hardness measurements, and microstructural analysis, Alloy 709 exhibits a stable performance in sodium application and its inherently higher strength will enhance its application for structural components in SFRs.

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1 Introduction

The Advanced Reactor Technologies campaign has focused on the sodium-cooled fast reactor concept because of its technical maturity. The current needs are for more reliable, more flexible, and more economical reactors suitable for commercial nuclear power generation. Research and development focuses on three areas including advanced materials, innovative components and systems, and computer modeling and simulation enabling predictions of long-term performance. Inherent in this research and development is the selection and adequate long-term performance of reactor structural materials that are directly exposed to the sodium coolant at elevated temperatures.

Figure 1-1 shows a schematic of a sodium-cooled fast reactor. In these reactors, heat is generated from fission reactions in a nuclear-fueled core. The heat is removed by liquid sodium flowing through the core, transferred to a steam system, and the steam is used to drive a turbine. Because of excellent heat transfer properties, liquid sodium has been selected as the coolant and heat transport medium. In general, austenitic stainless steels are used for the fuel cladding, in-core structural components, piping, and intermediate heat exchanger. High chromium ferritic steels are considered for primary piping system, intermediate heat exchanger, secondary piping and steam generator in SFRs. The selection of a particular material and combinations that will be used in both primary and secondary circuits is based upon a number of factors. For in-core applications, the stability of the material in the fast neutron environment and compatibility with the sodium coolant and the fuel (including possible fission-product interactions) are of primary concern. For out-of-core components such as reactor vessel, guard vessel, intermediate heat exchanger, etc. the compatibility with sodium environment and a long service life of 60 years are of primary importance. In the case of the steam generator, the resistance of the material to aqueous chloride and caustic cracking as well as minimization of corrosion wastage rates due to sodium-water reaction products in the event of a tube failure have important bearing on the material selection.

Figure 1-1. A schematic diagram of sodium-cooled fast reactor.

In general, structural materials can undergo a variety of interactions upon exposure to liquid sodium. The extent of interaction depends upon the exposure conditions of temperature, temperature gradient, sodium velocity and purity, the materials of construction, and external sources and sinks for the constituent elements of the structural materials. The interactions can be broadly classified into either metallic or nonmetallic element mass transfer. Metallic element mass transfer usually establishes a go/no-go type of evaluation of an alloy for use in sodium environment, based upon the established limits of material wastage or component section loss. A classic example of this is the unacceptable performance of vanadium base alloys in sodium of normal reactor purity. Upon selection of an alloy for sodium service, corrosion allowances that account for metallic element transfer can be incorporated into the design of specific components.

Nonmetallic elements such as oxygen, carbon, nitrogen, and hydrogen are known to migrate in structural materials/sodium systems as a result of chemical activity differences that occur in isothermal or non-isothermal systems. Transfer of these elements also occurs in systems where combinations of materials of different compositions are used. By examining the partitioning of nonmetallic elements between the structural alloy and sodium, the extent to which oxygen, carbon, and nitrogen interact in the structural material-sodium systems can be assessed. From the operation of the sodium fast reactor standpoint, the oxygen impurity in sodium can be controlled to ~1 wppm which would result in acceptable corrosion of austenitic and ferritic steels and nickel-base alloys at anticipated operating temperatures. The solubility of nitrogen in sodium is low in the reactor at the operating temperature, and its effect on materials performance may not be significant.

On the other hand, observations by various investigators that materials of nominally the same composition with different degrees of decarburization/carburization in sodium loops operating over similar temperature ranges have resulted in questions regarding the extrapolation of results obtained in small scale sodium loops to large reactor systems [Snyder et al. 1982]. Since carbon concentration in a given system is established by a dynamic equilibrium between the carbon sources and carbon sinks present in the system, it could vary from system to system as well as over time within a system. An analysis of the carburization-decarburization behavior of austenitic stainless steels in the primary heat-transport systems of the EBR-II and FFTF has been made that is based upon a kinetic model for the diffusion process and the surface area of steel in contact with flowing sodium at various temperatures in the two systems. In addition, the role of ingress of carbonaceous materials in altering the carbon concentration in sodium and its effect on materials performance has also been assessed.

It is necessary to evaluate and understand the influence of carbon in sodium on the microstructure and mechanical properties of advanced structural materials as well as establish the performance window for the materials in terms of temperature, carbon level in sodium, materials of construction, and ΔT in the sodium circuits. This report presents data on the corrosion, microstructural changes, and tensile properties of advanced Alloy 709, after exposure to sodium at temperatures in the range of 550-650°C. In addition, corrosion and microstructural aspects of Alloy 709 weldments are presented after exposures to flowing sodium environment.

Figure 1-2. Carburization-Decarburization regimes for Types 316 and 304L stainless steels in the FFTF and EBR-II primary sodium systems, respectively, in terms of the carbon concentration in sodium and temperature.

Table 2-1. Chemical composition (in wt%)

Alloy	Heat	Fe	C	Mn	P	S	Si	Ni	Cr	Mo	B	Ti	Nb	N	Al
709-01	120113806	Bal	0.05	1.0	<0.01	<0.01	0.39	24.5	20.9	1.5	0.003	0.07	0.23	0.19	-
709-02	011367	Bal	0.078	0.90	<0.005	<0.001	0.30	25.03	20.04	1.51	0.003	<0.01	0.26	0.17	-
709-05	011502	Bal	0.063	0.88	<0.005	<0.001	0.28	25.00	19.69	1.46	0.0022	<0.01	0.23	0.14	-
709-L	59776	Bal	0.066	0.91	0.014	-	0.44	24.98	19.93	1.51	0.0045	0.04	0.26	0.148	-
Alloy 625 Filler metal		5.0	0.10	0.50	0.015	0.015	0.50	58.0	20.0	9.0	-	0.40	3.15	-	0.40

Table 2-2. Heat treatment conditions.

Alloy	Heat No.	Heat treatment
709-01	120113806	Anneal at 1150°C for 30 min, water quenched
709-02	011367	Anneal at 1050°C for 30 min, water quenched
709-05	011502	Anneal at 1100°C for 120 min, water quenched
709-L	58776	Annealed at 1050 or 1100°C for 75 min or at 1150°C for 60 min, water quenched

2.2 Forced convection sodium loops

Two forced convection sodium loops were constructed at the Argonne National Laboratory (ANL) for sodium exposure tests of advanced materials. The Sodium Materials Test Loop 1 (SMT-1) (shown in Fig. 2-2(a)) consists of a single specimen-exposure vessel with an electromagnetic pump, two electromagnetic flow meters, an economizer, and a cold trap, with the total amount of sodium in the loop of approximately 10 kg. The vessel has large penetrations at the top for sample loading as well as small penetrations for a level probe, thermocouple, and argon/vacuum line. The maximum operating pressure and temperature of the specimen vessel are 5 psig and 700°C, respectively.

The Sodium Materials Test Loop 2 (SMT-2) (shown in Fig. 2-2(b)) is a dual sample-vessel loop for sodium exposure tests at two temperatures. The maximum operating pressure and temperature for the two sample vessels are 5 psig and 750°C, respectively, and the total amount of sodium in the loop is approximately 20 kg. Each vessel has two penetrations at the top for sample loading as well as smaller penetrations for a level probe, thermocouple, and argon/vacuum line.

Both loops are constructed of austenitic stainless steels. The oxygen content of the sodium is controlled by the cold trap in both loops. The temperature of the cold trap is maintained at 125°C to ensure that the oxygen concentration is at ~1 wppm during specimen exposure.

Figure 2-2. Isometric view of (a) the Sodium Materials Test Loop 1 (SMT-1) and (b) the Sodium Materials Test Loop 2 (SMT-2).

2.3 Sodium exposure experiments and post- exposure examinations

Specimens of the laboratory heats of Alloy 709 were exposed to flowing environment at temperatures of 550, 600, and 650°C for up to ~20,000 h. Table 2-3 gives the total exposure times at different exposure times for different heats of Alloy 709.

Table 2-3. Total sodium exposure times at 550, 600, and 650°C for different heats of Alloy 709.

Heat Identification	Total Exposure Time at 550°C (h)	Total Exposure Time at 600°C (h)	Total Exposure Time at 650°C (h)
709-01	-	-	5,143
709-02	-	4,394	26,075
709-05	-	-	11,059
709-L	-	-	-

After the sodium exposures, the specimens were removed from the loop for post-sodium-exposure examination. Specimens were cleaned with alcohol and final cleaning with water to remove any residual sodium. Specimen surfaces were visually inspected and recorded by a

digital camera, if needed. Mass and thickness measurements were made to determine the mass and thickness changes. Prior to and after each sodium exposure, each specimen was weighed three times using an OHAUS Model AP250 analytical balance to a precision of 10 μg ; the thickness of the specimen was measured three times using a micrometer to a precision of 0.0001 in. The post-sodium-exposure weight and thickness measurements were compared with the initial weight and thickness data obtained prior to Na exposure. If only non-destructive (weight and thickness) measurements were performed on a specimen, the specimen was reloaded into the sodium loop for continued exposure.

Destructive examinations after sodium exposures included microstructural characterization and tensile tests. The extended grip sections of the exposed tensile specimens were cut from both ends for microstructural analysis. Metallographic specimens were made from the cross section for examination of the specimen surface, microstructural characterization by optical microscopy (OM) and scanning electron microscopy (SEM), and micro-hardness measurements. The polished specimens of ferritic-martensitic steels were chemically etched with an etchant of 5 ml HNO_3 , 1 ml HF , and 50 ml H_2O . Thin foil specimens of 3-mm in diameter were made for microstructural characterization by transmission electron microscopy (TEM). Specimens were electropolished to perforation using a Tenupol twin-jet polishing unit.

Sodium-exposed sheet-type subsize tensile specimens were tested under uniaxial tension at the exposure temperature in an air furnace to examine the effect of sodium exposures on tensile properties. Figure 2-3 shows a setup for high temperature tensile tests in air at the Argonne National Laboratory. Tensile tests were performed in an electromechanical testing system equipped with a three-zone air furnace. The applied load was recorded by a load cell; the specimen displacement was measured by the crosshead extension. The engineering tensile properties were determined from analysis of load versus displacement data files. All the tests were conducted at a nominal strain rate, 0.001 s^{-1} .

Figure 2-3. Experimental setup for high temperature tensile tests.

3 Results

3.1 Corrosion behavior

The corrosion behavior of Alloy 709 in sodium was studied over the temperature range of 550-650°C at the oxygen level of ~1 wppm. Austenitic stainless steels, 709-01, 709-02, and 709-05 showed negligible weight loss at the exposure temperature of 650°C, and all the alloys showed similar weight loss behavior.

No measurable thickness changes were observed under any of the sodium-exposure conditions examined thus far. Specimens lost surface finish, but the surface remained smooth, and no spallation or surface deterioration was visually observable. This is expected behavior since the oxygen concentration is the primary cause for corrosion of materials and it was controlled to ~1 wppm in the current experiments. The weld specimens also showed negligible weight change upon sodium exposure at 650°C. Figure 3-1 shows the weight behavior of the alloys and welds as a function of sodium exposure at 650°C. Also shown in the figure are the data for Type 316 stainless steel exposed to sodium.

Figure 3-1. Weight changes as a function of exposure time for different heats of Alloy 709 and their weldments after sodium exposure at 650°C.

3.2 Effect of sodium exposure on microstructure

Austenitic alloys such as 316 stainless steel and Alloy 709, are generally subjected to a solution anneal treatment at high temperature such that all the alloying elements are initially in solution in austenite matrix. Upon aging at high temperature, phases such as $M_{23}C_6$, Sigma, Xi, Eta phases precipitate in grain boundaries and within the austenite matrix.

In Type 316 stainless steel (0.06C-18Cr-13Ni-2.4Mo-0.03N-Bal Fe), the phases that form are

- $M_{23}C_6$ ($M = Cr, Fe$)
- *Sigma* (Fe, Cr intermetallics)
- *Eta* (Laves phase Fe_2Mo)
- *Chi* (Fe, Cr, Mo intermetallics)

In Alloy 709 (0.05C-21Cr-25Ni-1.5Mo-0.25Nb-0.07Ti-0.19N), the phases that form are

- *Nb(CN)* in grain boundaries and within grains
- $M_{23}C_6$ ($M = Cr, Fe$)
- *Sigma* (Fe, Cr intermetallics)
- *G phase* ($Nb_6Ni_{16}Si_7$ particles, predominantly at 650°C and above)
- *Z phase* ($CrNbN$)

It is imperative to understand and quantify the time-temperature effect on the precipitation of various phases during aging and during sodium exposure of these austenitic alloys.

Figure 3-2 shows the SEM photomicrographs of cross section of Alloy 709-01 after 5,143 h exposure to sodium at 650°C. The alloy develops a very thin oxide scale on the surface and the near surface precipitates seem stable even after 5,143 hours in sodium. Figure 3-3 shows the elemental mapping of the alloy in cross section. Figure 3-4 shows the locations selected for EDX analysis in specimen exposed to sodium. Figure 3-5 shows concentrations of the constituent elements analyzed at various locations. Locations A, B, and C are indicative of base alloy composition, location D is at the triple point (enriched in Cr), location E is at the surface in an oxide layer, and locations F and G are particles that consist of high Cr with Mo and Si. Further analysis is planned along with ThermoCalc computations to assess the long term precipitation sequence in the alloy.

Figure 3-2. SEM photomicrographs of cross section of Alloy 709-01 after 5,143 h exposure to sodium at 650°C.

Figure 3-3. Elemental mapping for specimen of Alloy 709-01 after 5,143 h exposure to sodium at 650°C.

Figure 3-4. EDX analysis locations identified in photomicrographs for the specimen of Alloy 709-01 after 5,143 h exposure to sodium at 650°C.

Figure 3-5. EDX elemental analysis for Na, Si, Nb, Mo, Ti, Cr, Mn, Fe, Ni, and O for the specimen of Alloy 709-01 after 5,143 h exposure to sodium at 650°C.

3.3 Effect of sodium exposure on hardness

Cross-sectional specimens were prepared from the sodium-exposed specimens of Alloy 709 and examined by optical microscopy. The micro-hardness profiles were obtained in the thickness direction measured from the surface to beyond the central line up to ≈ 0.5 mm (the nominal thickness of the specimen, 0.76 mm). Figure 3-6a shows the hardness profiles for Alloy 709-01 Heat specimens in as received condition and after exposure to sodium at 650°C for 549, and 5143 h. A layer of slightly hardened layer zone was observed in the 549 h specimen, and seems to soften after 5143 h. Figure 3-6b shows the hardness profiles for Alloy 709-01 Heat specimens in as received condition, after exposure to sodium at 650°C for 5143 h, and after aging at 650°C for 5021 h. Very little variation in hardness is noted between the aged and sodium exposed specimens.

Figure 3-6. Vickers hardness profiles of Alloy 709-01 Heat specimens (a) after 0, 549 h, and 5143 h sodium exposure at 650°C and (b) after 0 h, 5143 h sodium exposure, and 5021 h aging at 650°C.

Figure 3-7 shows a comparison of Vickers hardness profiles of Alloy 709-01 Heat specimens with those for Type 316 stainless steel specimens after 0 h and 5143 h sodium exposure at 650°C. The results show that Alloy 709 is inherently stronger than Type 316 stainless steel and it maintains its strength even after sodium exposure. Figure 3-8 shows a comparison of Vickers hardness profiles of Alloy 709-02 Heat specimens (the new heat recently received) after 0 h and 2540 h sodium exposure at 650°C. These results indicate the hardness profiles for both heats of Alloy 709 are similar and little variation is noted after exposure to sodium.

Figure 3-7. A comparison of Vickers hardness profiles of Alloy 709-01 Heat specimens with those for Type 316 stainless steel specimens after 0 h and 5143 h sodium exposure at 650°C.

Figure 3-8. A comparison of Vickers hardness profiles of Alloy 709-02 Heat specimens after 0 h and 2540 h sodium exposure at 650°C.

3.4 Effect of sodium exposures on tensile properties

Table 3-1 summarizes the tensile properties of different heats of Alloy 709 in as-received condition and after exposure to flowing sodium environment at 650 and 600°C. Some of the details on the yield stress, ultimate tensile strength, uniform elongation, and total elongation, respectively, as a function of sodium exposure time for Alloy 709 have been presented in an earlier report [2].

In all heats of Alloy 709, the sodium exposure-induced changes in the yield stress and ultimate tensile strength were relatively small. The yield stress increased slightly and the ultimate tensile strength was nearly unchanged in 709-01 after sodium exposures for times up to ≈5000 h at 650°C. However, the alloys exhibited substantial uniform and total elongation even after 11,039 h of sodium exposure at 650°C. Additional specimens are being exposed to sodium at 600 and 550°C and will be tensile tested in the future. Figures 3-9 and 3-10 show a comparison of the effect of sodium exposure and thermal aging on various tensile properties of Alloy 709.

Table 3-1. Tensile properties of austenitic steels sodium exposed at 650 and 600°C.

Alloy	Na Exp. Cond.	Test T (°C)	YS (MPa)	UTS (MPa)	UE (%)	TE (%)
709-01	AR*	650	177	481	46	51
709-01	650°C – 549 h	650	213	462	33	38
709-01	650°C - 1008 h	650	222	463	30	41
709-01	650°C - 5143 h	650	228	471	25	34
709-02	AR	650	170	509	45	51.5
709-02	AR	650	173	513	51	57
709-02	AR	650	164	502	48	54
709-02	650°C – 2540 h	650	213	472	29	38.5
709-02	650°C – 2540 h	650	208	466	28	36
709-02	650°C – 4340 h	650	217	459	26.2	33.6
709-02	650°C – 4340 h	650	204	445	27	34.5
709-02	650°C – 8030 h	650	212	461	25.4	31.6
709-02	650°C – 9830 h	650	214	452	25.2	33.7
709-02	650°C – 9830 h	650	223	448	23	27
709-05	AR	650	177	491	40	49
709-05	AR	650	178	482	44	51
709-05	650°C – 3504 h	650	212	455	28	34
709-05	650°C – 8684 h	650	228	468	27	30
709-05	650°C – 8684 h	650	217	461	26.5	32.6
709-05	650°C – 11059 h	650	222	466	27.7	33.6
316H	AR	650	127	345	42	54
316H	650°C – 504 h	650	99	314	36	47
316H	650°C – 1008 h	650	109	325	32	47
316H	650°C - 2037 h	650	114	341	30	41
316H	650°C – 5143 h	650	125	357	33	40
316H	650°C – 7154 h	650	117	354	29	39
316H	650°C – 7154 h	650	137	367	29	43
316H	650°C – 8953 h	650	140	358	25	31
316H	650°C – 9982 h	650	165	395	25	32
316H	650°C – 18480 h	650	173	401	25	36
316H	650°C – 18480 h	650	157	398	26	34
316H	650°C – 24987 h	650	160	405	26	30
709-02	AR	600	600	169	521	46
709-02	AR	600	600	175	533	49.2
709-02	600°C – 4394 h	600	183	491	39	42

*AR: as-received

Figure 3-9. A comparison of thermal aging and sodium exposure on yield stress, ultimate tensile strength, uniform elongation, and total elongation as a function of exposure time for different heats of Alloy 709 tensile tested at 650°C.

Figure 3-10. A comparison of thermal aging and sodium exposure on yield stress, ultimate tensile strength, uniform elongation, and total elongation as a function of exposure time for Alloy 709-02 tensile tested at 600°C.

3.5 Tensile properties of Commercial heat of Alloy 709

Uniaxial tensile tests were performed on the solution annealed AOD, ESR, and ESR-Homogenized plates of commercial-size heat of Alloy 709-L. The tests were performed at room temperature in compliance with the ASTM E-8-15a standard. In all, 54 specimens were tested for the 9 plates (three melting practice and three solution-anneal temperatures). The specimens had a gauge diameter of 0.25" (6.35 mm) and a gauge length of 1.25" (31.8 mm). Additional details on the fabrication procedures, microstructural aspects, and hardness measurements are discussed in an earlier report [3].

Table 3-2 shows a listing of room temperature yield stress, ultimate tensile strength, total elongation, and reduction of area for the steel with different heat treatments and in rolling- and transverse directions. The results indicate that the properties are above the minimum required under the ASME Code Case for the commercial heat of NF709. The materials are being prepared for sodium exposure.

Table 3-2. Room temperature tensile properties of AOD, ESR, and ESR-Homogenized plates after different solution anneal treatments

Melt-Anneal T-Sp. Orientation	YS (MPa)	UTS (MPa)	TE (%)	RA (%)
AOD-1050-RD	403.8	724.9	42.7	64.2
AOD-1050-TD	374.8	715.4	40.7	58.7
AOD-1100-RD	350	714.5	47.8	70.6
AOD-1100-TD	346.6	714.8	47	67
AOD-1150-RD	336.9	724.6	47.8	74
AOD-1150-TD	376.9	712.5	48.2	69.9
ESR-1050-RD	372.3	740.5	41.6	67.7
ESR-1050-TD	400.1	728.3	39.3	63
ESR-1100-RD	356.7	732.7	45.6	72.4
ESR-1100-TD	356.7	723.7	46.7	67.9
ESR-1150-RD	287.1	664.4	48.9	72.4
ESR-1150-TD	325	694.1	44.1	70.4
ESR HOMO-1050-RD	486.1	802.6	32.6	52.1
ESR HOMO-1050-TD	437.4	760.5	37.5	59.8
ESR HOMO-1100-RD	390.2	761.9	43.1	68.3
ESR HOMO-1100-TD	381.7	743	43.9	66.1
ESR HOMO-1150-RD	334.4	725.8	44.4	73.4
ESR HOMO-1150-TD	352.3	734.3	46	69.5
NF 709 Commercial Heat	>270	>640	>30	-

3.6 Effect of sodium exposures on Alloy 709 weldments

Two different filler metals namely, Alloy 709 and Inconel 625, were used to fabricate weld of Alloy 709. The welded specimens were exposed to flowing sodium environment at 650°C for as long as 21,547 h. Table 3-3 lists the sodium exposure conditions for different weld specimens.

Table 3-3. A listing of weldment specimens and sodium exposure conditions

Specimen ID	Filler metal type	Temperature (°C)	Duration (h)	Exposure condition
W04 spare	IN625	As received	0	As received
W04A	IN625	650	1,800	Na
W04F	IN625	650	10,490	Na
W10I	Alloy 709	As received	0	As received
W01A	Alloy 709	650	5,490	Na
W01G	Alloy 709	650	10,877	Na
W01E	Alloy 709	650	21,547	Na

W01 Series (709 filled)

Hardness along the direction parallel to Na surface

Figure 3-11. Microstructures and hardness profiles in as-welded specimens of Alloy 709 after exposure to flowing sodium environment at 650°C.

Figure 3-12. Hardness profiles in as-welded specimens of Alloy 709 after exposure to flowing sodium environment at 650°C.

About 25 μm near the sodium surface there is a noticeable difference in microstructure, showing up in both base metal and weld, indicating possible effect from sodium.

Figure 3-13. Microstructures of sodium-affected surface region of weld specimens after sodium exposure at 650°C.

Weld Metallography

W01E Na 650C 21547h (etched)

Pattern observed in the weld is a collection of small dimples

Figure 3-14. Optical micrographs of weld region after 21,547 h exposure to sodium at 650°C.

4 Summary

This report provides an update on the understanding of the effects of sodium exposures on tensile properties of advanced alloy 709 in support of the design and operation of structural components in sodium-cooled fast reactors (SFRs). The report is a Level 3 deliverable in FY17 (M3AT-17AN1602093), under the Work Package AT-17AN160209, “Sodium Compatibility” performed by Argonne National Laboratory (ANL), as part of Advanced Reactor Technologies Program.

Three laboratory-size heats of Alloy 709 austenitic steel were investigated in liquid sodium environments at 550-650°C to understand its corrosion behaviour, microstructural evolution, and tensile properties. In addition, a commercial scale heat has been produced and hot-rolled into plates.

- All the heats of Alloy 709 exhibited negligible weight loss at the exposure temperature of 650°C, and all the alloys showed similar weight loss behavior.
- The hardness profiles of sodium exposed Alloy 709 specimens showed little variation after $\approx 5,000$ h sodium exposure and were comparable to those obtained with thermally aged specimens. However, the hardness values for Alloy 709 were significantly higher than for Type 316 stainless steel after sodium exposure indicating the inherent higher strength for Alloy 709 and its retention of the strength even after sodium exposure.
- Microstructural analysis of the ≈ 5000 h sodium-exposed Alloy 709 specimens showed stable microstructures and the fine precipitate morphology, indicating limited mass transport between the alloy and sodium at 650°C.

- Currently, long term exposures of specimens from laboratory heats are being conducted at 600 and 550°C to supplement the data developed after sodium exposure at 650°C.
- A commercial-scale heat of Alloy 709 has been procured and detailed analysis of the material exhibit tensile properties that exceed the minimum values specified in the ASME Code Case for commercial heat of NF709. The material from this heat will be exposed to sodium environment to validate its performance.
- Based on the sodium compatibility studies, in terms of tensile properties, hardness measurements, and microstructural analysis, Alloy 709 exhibits a stable performance in sodium application and its inherently higher strength will enhance its application for structural components in SFRs.

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