Report on the completion of the procurement of the first heat of Alloy 709

Nuclear Engineering Division

About Argonne National Laboratory

Argonne is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC under contract DE-AC02-06CH11357. The Laboratory's main facility is outside Chicago, at 9700 South Cass Avenue, Argonne, Illinois 60439. For information about Argonne and its pioneering science and technology programs, see www.anl.gov.

DOCUMENT AVAILABILITY

Online Access: U.S. Department of Energy (DOE) reports produced after 1991 and a growing number of pre-1991 documents are available free via DOE's SciTech Connect (<http://www.osti.gov/scitech/>)

Reports not in digital format may be purchased by the public from the National Technical Information Service (NTIS):

U.S. Department of Commerce
National Technical Information
Service 5301 Shawnee Rd
Alexandria, VA 22312
www.ntis.gov
Phone: (800) 553-NTIS (6847) or (703) 605-6000
Fax: (703) 605-6900
Email: **orders@ntis.gov**

Reports not in digital format are available to DOE and DOE contractors from the Office of Scientific and Technical Information (OSTI):

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
www.osti.gov
Phone: (865) 576-8401
Fax: (865) 576-5728
Email: **reports@osti.gov**

Disclaimer

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor UChicago Argonne, LLC, nor any of their employees or officers, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of document authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof, Argonne National Laboratory, or UChicago Argonne, LLC.

Report on the completion of the procurement of the first heat of Alloy 709

Prepared by

K. Natesan, X. Zhang, and T.-L. Sham

Nuclear Engineering Division

Argonne National Laboratory

H. Wang

Oak Ridge National Laboratory

June 2017

ABSTRACT

This report provides details on the completion of the procurement of the first commercial-sized heat of Alloy 709. The report is a Level 3 deliverable in FY17 (M3AT-17OR1602053), under the Work Package AT-17OR160205, “Advanced Alloy Development” performed by Oak Ridge National Laboratory, as part of Advanced Structural Materials Program for the Advanced Reactor Technologies (ART).

This work project supports the fabrication scale up effort for Alloy 709 that was started in FY16. The effort culminated in the placement of a Purchase Order in August 2016 with a commercial vendor to melt an Alloy 709 heat using industrial melt practice. Four ingots, totaling about 45,000 lb, had been bottom-poured from the melt in September 2016. Two of the ingots were hot rolled into 1.2”x60”x155” and 1.1”x60”x100” plates using standard hot rolling process in FY17. Some small test pieces were cut from the as-rolled plates and sent to Argonne National Laboratory (ANL) for archival. The plates were then heat treated and surface pickled by the vendor. The plates were subsequently delivered to ANL and Oak Ridge National Laboratory (ORNL).

Properties and microstructure screening were performed on these plates upon delivery in February 2017 at ANL. Several samples were cut from the as-rolled and heat-treated plates and were analyzed for their microstructures, hardness values, grain sizes, and room temperature tensile properties. The results indicate that the scaled-up heat of Alloy 709 fabricated using commercial practice exhibit tensile properties that exceed the minimum values specified in the ASME Code Case for commercial heat of NF709. These plates will be used to support base metal testing for the 650°C, 100,000-h Alloy 709 Code Case development, for fabrication of weldments, and for the NEUP projects.

TABLE OF CONTENTS

ABSTRACT.....	ii
TABLE OF CONTENTS.....	iii
LIST OF TABLES.....	iv
LIST OF FIGURES	v
1 Introduction	1
2 Material Procurement.....	3
2.1 Statement of Work	3
2.2 Melting and Fabrication rocedure.....	3
3 Materials Properties.....	8
3.1 Microstructure of as-rolled plates	9
3.2 Hardness Profiles of As-Rolled Plates.....	11
3.3 Microstructure of Solution Annealed plates	11
3.4 Hardness Profiles of Solution Annealed Plates	18
3.5 Tensile Properties of Solution Annealed Plates.....	18
4 Summary	26
Acknowledgement	26
References.....	27

LIST OF TABLES

Table 2-1. Chemical composition of melt of Alloy 709 heat # 58776 (in wt%).....	3
Table 3-1. Measured grain sizes in AOD, ESR, and ESR-Homogenized plates after solution anneal treatments.....	17
Table 3-2 Room temperature tensile properties of AOD, ESR, and ESR- Homogenized plates after different solution anneal treatments.....	24

LIST OF FIGURES

Figure 2-1.	Alloy 709-20" diameter ingots (non-homogenized and homogenized) stored at ANL	4
Figure 2-2.	Vendor-supplied chemical analyses of ingots, used for the fabrication of plates.....	5
Figure 2-3.	Photographs of typical plates of hot-rolled Alloy 709 plates in as-rolled condition	6
Figure 2-4.	Photographs of 1.2" thick (AOD) and 1.1" thick (ESR, homogenized and non-homogenized) plates after pickling and surface cleaning	8
Figure 3-1.	Optical micrographs of the microstructures of as-rolled AOD plate in thickness direction.....	9
Figure 3-2.	Optical micrographs of the microstructures of as-rolled ESR plate in thickness direction	10
Figure 3-3.	Optical micrographs of the microstructures of as-rolled ESR-Homogenized plate in thickness direction	10
Figure 3-4.	Hardness profiles of as-rolled AOD, ESR, and ESR-Homogenized plates in the thickness direction.....	11
Figure 3-5.	Optical micrographs of the microstructures of AOD plates in the thickness direction after solution anneal treatment at 1050°C (1922°F), 1100°C (2012°F), and 1150°C (2102°F)	13
Figure 3-6.	Optical micrographs of the microstructures of ESR plates in the thickness direction after solution anneal treatment at 1050°C (1922°F), 1100°C (2012°F), and 1150°C (2102°F)	15
Figure 3-7.	Optical micrographs of the microstructures of ESR-Homogenized plates in the thickness direction after solution anneal treatment at 1050°C (1922°F), 1100°C (2012°F), and 1150°C (2102°F)	17
Figure 3-8.	Hardness profiles of AOD, ESR, and ESR-Homogenized plates in the thickness direction after solution anneal at 1050, 1100, and 1150°C.....	18
Figure 3-9.	Schematic drawing of the plate that is used to fabricate ASTM-size tensile specimens in the rolling direction and in the transverse direction.	19
Figure 3-10.	Schematic of tensile specimen used for generating tensile data on Alloy 709	20
Figure 3-11.	Yield stress (0.2% offset) and ultimate tensile strength for AOD, ESR, and ESR-homogenized Alloy 709 at room temperature	21
Figure 3-12.	(Total elongation and reduction of area for AOD, ESR, and ESR-homogenized Alloy 709 at room temperature.....	22

Figure 3-13. Average of three values of yield stress and ultimate tensile strength for AOD, ESR, and ESR-homogenized Alloy 709 at room temperature.	23
Figure 3-14. Average of three values of total elongation and reduction of area for AOD, ESR, and ESR-homogenized Alloy 709 at room temperature	24

1 Introduction

Advanced materials are a key element in the development of advanced nuclear energy systems. High-performance structural materials allow for a compact and simple design of the reactor structure, and have the potential to reduce the construction and operational costs for next-generation advanced nuclear reactors. Due to the significant enhancement in time-dependent mechanical properties of the austenitic stainless steel Alloy 709 relative to 316H stainless steel, a reference construction material for SFR systems, code qualification of Alloy 709 was recommended (Sham et al. 2015). A comprehensive plan for the development of a 500,000-hour, 760°C ASME Code Case and the resolution of licensing issues for Alloy 709 was developed in FY15. A Phase I implementation of this plan that includes a 100,000-hour, 650°C ASME code case and the initiation of very long term creep tests, thermal aging, and sodium exposure of Alloy 709 was established.

Alloy 709 is derived from NF709 (Fe-20Cr-25Ni-1.5Mo-Nb,B,N), which was a commercial heat- and corrosion- resistant austenitic stainless steel developed by Nippon Steel Corporation in Japan for boiler tubing applications. The high strength of NF709 is achieved by controlling the carbon content to 0.07–0.10% and precipitation strengthening by NbC and CrNbN (Z phase). NF709 also shows good fabricability properties and weldability. It is regarded as one of the best austenitic steels for elevated temperature applications among commercially-available austenitic alloy classes. The NF709 alloy provides time dependent strength nearly double that for conventional 304 and 316 stainless steels at sodium-cooled fast reactor relevant temperatures (Busby et al 2008). While the cost for this alloy has been estimated at approximately 2-4 times that for 304 SS (and 1.5 to 3 times that for 316 SS), many fossil plants have found that the improved performance outweighs the commodity cost, and is still far below the cost for Ni-based superalloys at comparable strengths. Alloy 709 has the same chemical composition as NF709 but is intended for sodium fast reactor applications that include reactor vessel, core supports, primary and secondary piping, and possibly intermediate heat exchanger and compact heat exchanger. Hence development of processing conditions and fabrication scale up for different product forms such as plates, pipes, bars, forgings and sheets, in addition to seamless tubing, are required.

One of the major concerns in applications of the advanced alloys in sodium-cooled fast reactors is their long-term microstructural stability and associated degradation of mechanical properties during service. Previous work (Li, et al. 2010–2013) has showed that tensile properties of these advanced materials degrade with time, when exposed to high temperatures and liquid sodium. Significant microstructural changes during prolonged thermal and sodium exposures can lead to dramatically different responses to service environments.

The objective of this project is to support the fabrication scale up effort for Alloy 709 that was started in FY16. The effort culminated in the placement of a Purchase Order in August 2016 by Oak Ridge National Laboratory (ORNL) with a commercial vendor to melt an Alloy 709 heat using industrial melt practice. Four ingots, totaling about 45,000 lb, had been bottom-poured from the melt in September 2016. The ingots were rolled into plates which were subsequently delivered to ANL and ORNL. Several samples were cut from the as-rolled test pieces and heat treated plates and were analyzed for their microstructures, hardness values, grain sizes, and tensile properties. The results indicate that the scaled up heat of Alloy 709 fabricated using

commercial practice exhibit tensile properties that exceed the minimum values specified in the ASME Code Case for commercial heats of NF709.

2 Materials Procurement

2.1 Statement of Work

U.S. Department of Energy, Office of Nuclear Energy's Advanced Reactor Technologies Program is conducting R&D on qualifying an advanced austenite stainless steel, Alloy 709, for ASME Section III Division 5 constructions in support of development and deployment of sodium fast reactors.

The product chemistry shall conform to the ranges or maximum values specified in wt % in Table 1. The chemistry aims and the actual melt compositions are also shown in the table.

Table 2-1. Chemical composition of melt of Alloy 709 heat # 58776 (in wt%)

Alloy 709	C	Cr	Ni	Mn	Mo	N	Si	P	Ti	Nb	B	Fe
Specification range	0.04-0.10	19.5-23	23-26	1.5	1.0-2.0	0.14-0.16	1.0	<0.025	0.2	0.1-0.4	0.002-0.01	Bal
Aim	0.07	20	25	0.9	1.5	0.15	0.40	*	0.05	0.25	0.002-0.005	Bal
Actual	0.066	19.93	24.98	0.91	1.51	0.148	0.44	0.014	0.04	0.26	0.0045	Bal

*The P shall not exceed 0.025 wt%.

2.2 Melting and Fabrication Procedure

The master heat was produced to provide the project with sufficient material under different processing conditions such as Argon-Oxygen-Decarburization (AOD), Electroslag Remelting (ESR), and Electroslag Remelting with subsequent Homogenization.

AOD is a process primarily used in stainless steel making and other high grade alloys with oxidizable elements such as chromium and aluminum. After initial melting, the metal is transferred to an AOD vessel where it is subjected to three steps of refining; decarburization, reduction, and desulphurization.

ESR is a process of remelting and refining steel for making high quality ingots. The ESR process uses the as-cast alloy as a consumable electrode. Electric current is passed between the electrode and the new ingot, which is formed in the bottom of a water-cooled copper mold. The new ingot is covered in an engineered slag that is superheated by the electric current. The electrode tip is slowly melted from contact with the slag. These metal droplets travel through the slag to the bottom of the water-cooled mold and slowly freeze as the ingot is directionally solidified upwards from the bottom of the mold. The slag pool floats above the refined alloy, continuously floating upwards as the alloy solidifies. The molten metal is cleaned of impurities that chemically react with the slag or otherwise float to the top of the molten pool as the molten droplets pass through the slag.

The master heat melt was to produce the following ingots:

1. one (1) AOD slab, approximately 13"x42" cross-section
2. one (1) ESR slab, approximately 12"x42" cross-section
3. two (2) ESR round ingots, 20" diameter

The ESR slab was sectioned into two-halves. One of the halves was homogenized at 2192°F (1200°C) for 48 hours and water quenched.

One of the ESR 20" diameter ingot was homogenized at 2192°F (1200°C) for 48 hours and water quenched. Figure 1 shows the ESR ingots (one non-homogenized and another homogenized) that were shipped by the vendor to ANL and are currently being stored in Building 212 in ANL. Figure 2 gives the vendor-supplied composition of the two ingots used for the fabrication of slabs. In the figure, 58776-1R T and B correspond to the top and bottom, respectively, of 1R ingot. Similarly, 58776-2R T and B correspond to the top and bottom, respectively, of 2R ingot.

Figure 2-1. Alloy 709-20" diameter ingots (non-homogenized and homogenized) stored at ANL.

PRODUCT	709				DATE				10/19/16			
HEAT NUMBER	C	Mn	P	S	Si	Cr	Ni	Mo	Cu	Co	Ti	Al
58776 -2R T	0.068	0.91	0.014	0.001	0.39	20.06	25.11	1.51	0.06	0.02	0.02	0.01
58776 -2R B	0.066	0.90	0.014	0.001	0.41	20.03	25.08	1.51	0.06	0.02	0.01	0.02
TEST METHOD	LECO	XRF	XRF	LECO	O.E.	XRF	XRF	XRF	XRF	O.E.	O.E.	O.E.
HEAT NUMBER	B	Nb	N	Sn	V	W	Pb	Fe	O	Ta	Mg	Zr
58776 -2R T	0.0042	0.26	0.151	0.002	0.03	<0.015	<0.0010	BAL				
58776 -2R B	0.0026	0.25	0.151	0.003	0.03	<0.015	<0.0010	BAL				
TEST METHOD	O.E.	XRF	LECO	O.E.	O.E.	O.E.	O.E.					

ANL-ART-89

Figure 2-3. Photographs of typical plates of hot-rolled Alloy 709 plates in as-rolled condition.

The AOD slab was hot-rolled continuously, without reheating, per vendor plate-mill practice to three (3) 1.20" thick plates (see Figure 3 for typical as-rolled plates).

The starting hot rolling temperature was around 2192°F (1200°C). Each plate was solution annealed at a different temperature. After solution anneal, the plates were water-quenched, iron grit blasted, and roller leveled. Surfaces were pickled. The dimensions, solution anneal temperatures and approximate weights of the plates are:

One (1) 1.20" x 60" RW x 155" RL plate, approximately 3,299 lbs, solution annealed at 1,922°F (1050°C)

One (1) 1.20" x 60" RW x 155" RL plate, approximately 3,299 lbs, solution annealed at 2,012°F (1100°C)

One (1) 1.20" x 60" RW x 155" RL plate, approximately 3,299 lbs, solution annealed at 2,102°F (1150°C)

Each finished plate was cut into two pieces, each piece will be approximately 1.20" x 60" RW x 77" RL. Each plate was marked in (2) places with grade, heat number, gauge, size, heat treat condition and final rolling direction.

The ESR slab was hot-rolled continuously, without reheating, per the vendor plate-mill practice to three (3) 1.10" thick plates. The starting hot rolling temperature was around 2192°F

(1200°C). Each plate was solution annealed at a different temperature. After solution anneal, the plates were water-quenched, iron grit blasted, and roller leveled. Surfaces were pickled. The dimensions, solution anneal temperatures and approximate weights of the plates are:

- One (1) 1.10" x 60" RW x 100" RL plate, approximately 1,951 lbs, solution anneal at 1,922°F (1050°C)
- One (1) 1.10" x 60" RW x 100" RL plate, approximately 1,951 lbs, solution anneal at 2,012°F (1100°C)
- One (1) 1.10" x 60" RW x 100" RL plate, approximately 1,951 lbs, solution anneal at 2,102°F (1150°C)

Each finished plate was cut into two pieces, each piece of approximately 1.10" x 60" RW x 50" RL. Each piece was marked in (2) places with grade, heat number, gauge, size, heat treat condition and final rolling direction.

The ESR-Homogenized slab was hot-rolled continuously, without reheating, per the vendor plate-mill practice to three (3) 1.10" thick plates. The starting hot rolling temperature was around 2192°F (1200°C). Each plate was solution annealed at a different temperature. After solution anneal, the plates were water-quenched, iron grit blasted, and roller leveled. Surfaces were pickled. The dimensions, solution anneal temperatures and approximate weights of the plates are:

- One (1) 1.10" x 60" RW x 100" RL plate, approximately 1,951 lbs, solution anneal at 1,922°F (1050°C)
- One (1) 1.10" x 60" RW x 100" RL plate, approximately 1,951 lbs, solution anneal at 2,012°F (1100°C)
- One (1) 1.10" x 60" RW x 100" RL plate, approximately 1,951 lbs, solution anneal at 2,102°F (1150°C)

Each finished plate was cut into two pieces, each piece of approximately 1.10" x 60" RW x 50" RL. Each piece was marked in (2) places with grade, heat number, gauge, size, heat treat condition and final rolling direction.

Half of the plates fabricated from the ESR ingot was solution annealed at three different temperatures to evaluate their microstructures as function of annealing condition. The solution anneal conditions were as follows:

- 1,922°F (1050°C) – 75 minutes
- 2,012°F (1100°C) – 75 minutes
- 2,102°F (1150°C) – 60 minutes

See Figure 4 for the photograph of finished plates. The two as-cast ESR ingots and half the AOD, ESR, and ESR-homogenized as-rolled and finished plates were shipped to ANL and the other half of the plates were shipped to ORNL.

Figure 2-4. Photographs of 1.2" thick (AOD) and 1.1" thick (ESR, homogenized and non-homogenized) plates after pickling and surface cleaning.

3 Materials Properties

The AOD, ESR, and ESR-Homogenized plates were examined to characterize the microstructures, grain size, hardness, and room temperature tensile properties. Optical metallography was used to obtain the microstructures in the thickness direction of the plates. Grain size measurements were also made using grain intercept method in the equiaxed regions of the microstructures. In addition, mechanical properties of the solution annealed materials will be determined to establish the optimum solution anneal temperature. Vickers hardness measurements were made on the plates in the thickness direction using Buehler Micromet 2000 Series Microhardness tester. Uniaxial tensile tests were constructed using ASTM size specimens as per the Standard ASTM E-8-15a.

3.1 Microstructure of As-Rolled Plates

Figure 3-1 shows the optical micrographs of the microstructures of as-rolled AOD plates in the thickness direction. Figures 3-2 and 3-3 show the optical micrographs of as-rolled ESR and ESR-homogenized materials, respectively, in thickness direction. It is evident that the microstructures show a distribution of small and large grains, especially in the near surface regions of the plates. The ESR homogenized plate seem to have some recrystallization due to the elevated temperature homogenization treatment of the ingot.

Figure 3-1. Optical micrographs of the microstructures of as-rolled AOD plate in thickness direction.

Figure 3-2. Optical micrographs of the microstructures of as-rolled ESR plate in thickness direction.

Figure 3-3. Optical micrographs of the microstructures of as-rolled ESR-Homogenized plate in thickness direction.

3.2 Hardness Profiles of As-Rolled Plates

Figure 3-4 shows the Vickers hardness profiles for the as-rolled AOD, ESR, and ESR-Homogenized plates in the thickness direction. The thicknesses of the AOD plate was 30.5 mm whereas the thickness of ESR and ESR-Homogenized plates was 27.9 mm.

Figure 3-4. Hardness profiles of as-rolled AOD, ESR, and ESR-Homogenized plates in the thickness direction.

3.3 Microstructure of Solution Annealed Plates

Figure 3-5 shows the optical micrographs of the microstructures of AOD plates in the thickness direction after solution anneal treatment at 1050°C (1922°F), 1100°C (2012°F), and 1150°C (2102°F). Figures 3-6 and 3-7 show the similar optical micrographs of solution annealed ESR and ESR-homogenized materials, respectively, in thickness direction. It is evident that for all the plates (AOD, ESR, and ESR-Homogenized) solution annealing at 1050°C does not result in full recrystallization of the material and significant banding is observed. On the other hand, a solution anneal treatment at 1100°C results in almost complete recrystallization and fully developed equiaxed grain structure. The grain size measurements were made in the equiaxed regions of the structures and the values are listed in Table 3.1. Solution anneal at 1150°C seems to cause some coarsening of the grains, primarily in AOD plates.

AOD Specimen ID: 58776-4-A1 Annealed at 1922°F (1050°C)

**AOD Specimen ID: 58776-4-B1
Annealed at 2012°F (1100°C)**

Figure 3-5. Optical micrographs of the microstructures of AOD plates in the thickness direction after solution anneal treatment at 1050°C (1922°F), 1100°C (2012°F), and 1150°C (2102°F).

ESR Specimen ID: 58776-RBA-11
Annealed at 1922°F (1050°C)

ESR Specimen ID: 58776-RBB-11
Annealed at 2012°F (1100°C)

Figure 3-6. Optical micrographs of the microstructures of ESR plates in the thickness direction after solution anneal treatment at 1050°C (1922°F), 1100°C (2012°F), and 1150°C (2102°F).

ESR Homogenized Specimen ID: 58776-RAA-11
Annealed at 1922°F (1050°C)

ESR Homogenized Specimen ID: 58776-RAB-11
Annealed at 1012°F (540°C)

Figure 3-7. Optical micrographs of the microstructures of ESR-Homogenized plates in the thickness direction after solution anneal treatment at 1050°C (1922°F), 1100°C (2012°F), and 1150°C (2102°F).

Table 3-1. Measured grain sizes* in AOD, ESR, and ESR-Homogenized plates after solution anneal treatments

Melt Process	Solution Anneal Temperature (°C)		
	1050	1100	1150
AOD	21 μm	37 μm	42 μm
ESR	18 μm	29 μm	29 μm
ESR-Homogenized	19.5 μm	35 μm	36 μm

*The grain size values listed above are based on measurements made only in the equiaxed regions.

3.4 Hardness Profiles of Solution Annealed Plates

Figure 3-8 shows the Vickers hardness profiles for the AOD, ESR, and ESR-Homogenized plates in the thickness direction, after solution anneal treatment at 1050, 1100, and 1150°C. The thicknesses of the AOD plate was 30.5 mm whereas the thickness of ESR and ESR-Homogenized plates was 27.9 mm. The hardness values in these plots are average of two scans in each plate in the thickness direction. It is evident that the Vickers hardness values through thickness is in the range of ~180-230 for all the plates.

Figure 3-8. Hardness profiles of AOD, ESR, and ESR-Homogenized plates in the thickness direction after solution anneal at 1050, 1100, and 1150°C

3.5 Tensile Properties of Solution Annealed Plates

Uniaxial tensile tests were performed on the solution annealed AOD, ESR, and ESR-Homogenized plates. 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). Figure 3-9 shows the locations on the plate where the specimens (in the rolling and transverse directions of the plate) were machined. Figure 3-10 shows a schematic of the drawing used in the fabrication of the specimens. The specimens had a gauge diameter of 0.25" (6.35 mm) and a gauge length of 1.25" (31.8 mm).

Figure 3-11 shows bar graphs of yield stress and ultimate tensile strength at room temperature for AOD, ESR, and ESR-Homogenized plates after different solution anneal treatments. Figure 3-12 shows bar graphs of total elongation and reduction of area at room temperature for AOD, ESR, and ESR-Homogenized plates after different solution anneal treatments. Figures 3-13 and 3-14 show the average values of the properties for of the three specimens in the rolling and transverse directions after different solution anneal treatments. Table 3-2 shows a listing of YS, UTS, TE, and RA values for different specimens. The results indicate that the properties are above the minimum required under the ASME Code Case for the commercial heat of NF709.

Figure 3-9. Schematic drawing of the plate that is used to fabricate ASTM-size tensile specimens in the rolling and transverse directions.

Figure 3-10. Schematic of tensile specimen used for generating tensile data on Alloy 709.

Figure 3-11. Yield stress (0.2% offset) and ultimate tensile strength for AOD, ESR, and ESR-homogenized Alloy 709 at room temperature.

Figure 3-12. Total elongation and reduction of area for AOD, ESR, and ESR-homogenized Alloy 709 at room temperature.

Figure 3-13. Average of three values of yield stress and ultimate tensile strength for AOD, ESR, and ESR-homogenized Alloy 709 (in rolling and transverse directions) at room temperature for different solution anneal treatments.

Figure 3-14. Average of three values of total elongation and reduction of area for AOD, ESR, and ESR-homogenized Alloy 709 (in rolling and transverse directions) at room temperature for different solution anneal treatments.

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	-

4 Summary

This report provides details on the completion of the procurement of the first commercial-sized heat of Alloy 709. The report is a Level 3 deliverable in FY17 (M3AT-17OR1602053), under the Work Package AT-17OR160205, “Advanced Alloy Development” performed by Oak Ridge National Laboratory, as part of Advanced Structural Materials Program for the Advanced Reactor Technologies (ART).

This work project supports the fabrication scale up effort for Alloy 709 that was started in FY16. The effort culminated in the placement of a Purchase Order in August 2016 with a commercial vendor to melt an Alloy 709 heat using industrial melt practice. Four ingots, totaling about 45,000 lb, had been bottom-poured from the melt in September 2016. Two of the ingots were hot rolled into 1.2”x60”x155” and 1.1”x60”x100” plates using standard hot rolling process in FY17. Some small test pieces were cut from the as-rolled plates and sent to Argonne National Laboratory (ANL) for archival. The plates were then heat treated and surface pickled by the vendor. The plates were subsequently delivered to ANL and Oak Ridge National Laboratory (ORNL).

Properties and microstructure screening were performed on these plates upon delivery in February 2017 at ANL. Several samples were cut from the as-rolled and heat-treated plates and were analyzed for their microstructures, hardness values, grain sizes, and room temperature tensile properties. The results indicate that the scaled-up heat of Alloy 709 fabricated using commercial practice exhibit tensile properties that exceed the minimum values specified in the ASME Code Case for commercial heat of NF709. These plates will be used to support base metal testing for the 650°C, 100,000-h Alloy 709 Code Case development, for fabrication of weldments, and for the NEUP projects.

Acknowledgement

This research was sponsored by the U.S. Department of Energy (DOE) under Contract DE-AC02-06CH11357 with the Argonne National Laboratory (ANL), and Contract DE-AC05-00OR22725 with the Oak Ridge National Laboratory. Programmatic direction was provided by the Office of Advanced Reactor Technologies (ART) of the Office of Nuclear Energy (NE). We gratefully acknowledge the support provided by Brian Robinson of DOE-NE, ART Program Manager; William Corwin of DOE-NE, ART Materials Technology Lead; and Robert Hill of ANL, ART Co-National Technical Director, and Christopher Grandy of ANL, ART Fast Reactors Technical Area Lead.

Cooperation from Tom Wood of G.O. Carlson is gratefully acknowledged. David Rink and Ronald Clark of ANL are thanked for assisting in metallography and in hardness measurements.

References

Busby, J. T., S. Byun, R. Klueh, P. Maziasz, and J. Vitek, K. Natesan, M. Li, R. Wright, S. Maloy, M. Toloczko, A. Motta, B. D. Wirth, G. R. Odette, and T. Allen, "Candidate Developmental Alloys for Improved Structural Materials for Advanced Fast Reactors," ORNL/GNEP/LTR-2008-023, March 2008.

Li, M, Argonne National Laboratory, unpublished information, 2013.

Li, M., Argonne National Laboratory, unpublished information, 2011.

Li, M., Argonne National Laboratory, unpublished information, 2010.

***Division**

Argonne National Laboratory
9700 South Cass Avenue, Bldg. *#
Argonne, IL 60439

www.anl.gov

Argonne National Laboratory is a U.S. Department of Energy
laboratory managed by UChicago Argonne, LLC