ORNL/TM-2020/1693

Report on FY 2020 Testing of Alloy 709 in Support of EPP Analysis

Yanli Wang

October 2020

Approved for public release.
Distribution is unlimited.

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

ORNL/TM- 2020/1693

Materials Science and Technology Division

REPORT ON FY 2020 TESTING OF ALLOY 709 IN SUPPORT OF EPP ANALYSIS

Yanli Wang

October 2020

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, TN 37831-6283
managed by
UT-BATTELLE, LLC
for the
US DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS, ACRONYMS, AND INITIALISMS

ANL	Argonne National Laboratory
ART	Advanced Reactor Technologies
ASME	American Society of Mechanical Engineers
CC	Code Case
CF	creep-fatigue
DOE	Department of Energy
EPP	Elastic-Perfectly Plastic
ESR	electroslag remelt
INL	Idaho National Laboratory
MCR	Minimum Creep Rate
NE	Office of Nuclear Energy
ORNL	Oak Ridge National Laboratory
SA	solution-annealing or solution-annealed
SFR	sodium fast reactor

ACKNOWLEDGMENTS

This research was sponsored by the US Department of Energy (DOE), Office of Nuclear Energy (NE), under contract DE-AC05-00OR22725 with Oak Ridge National Laboratory (ORNL), managed and operated by UT-Battelle LLC. Programmatic direction was provided by the Office of Nuclear Reactor Deployment of DOE NE.

The author gratefully acknowledges the support provided by Brian Robinson, DOE-NE, Federal Manager, Fast Reactors Campaign, Advanced Reactor Technologies (ART) Program; Sue Lesica, Federal Manager, Advanced Materials, ART Program; and Robert Hill of Argonne National Laboratory (ANL), National Technical Director, Fast Reactors Campaign, ART Program, and T.-L. Sham of ANL, Technology Area Lead, Advanced Materials, ART Program.

The author also wishes to thank ORNL staff members C. Shane Hawkins and Jeremy Moser for their technical support in carrying out the experiments, and Lianshan Lin and Jian Chen for reviewing this report.

ABSTRACT

Research activities in support of the development of a 500,000 hr, 760°C ASME Code Case (CC) for Alloy 709 are ongoing at Oak Ridge National Laboratory (ORNL), Argonne National Laboratory, and Idaho National Laboratory. Integration of the simplified Elastic-Perfectly Plastic (EPP) methods for the design of Alloy 709 reactor components is a requirement for the Alloy 709 CC.

This report documents the research plans and initiation of testing in support of integrating EPP analysis methods for Alloy 709 at ORNL in FY 2020. Tests are designed and initiated to evaluate the effect of cyclic loading on the creep properties of Alloy 709. The preliminary results show that cyclic loading has an insignificant effect on the minimum creep rate, although additional tests are recommended to confirm this conclusion. A preliminary testing plan for multi-axial creep rupture has been established and the specimens are machined. Execution of the testing plan will continue in FY 2021.

1. INTRODUCTION

Nuclear power contributes significantly to meeting the nation's energy, economic, environmental, and national security needs. The sodium fast reactor (SFR) is a leading candidate for recycling of used fuel to close the fuel cycle and for power generation. While SFR technology is relatively mature, improvements in its capital cost and economic return must be made before the private sector will invest in large-scale, commercial deployment of SFRs.

Because of the superior mechanical properties of the austenitic stainless-steel Alloy 709 relative to 316H, a reference construction material for SFR systems, code qualification of Alloy 709, was recommended in FY 2014. A comprehensive plan was established in FY 2015 for the development of a 500,000 hr, 760°C ASME Code Case (CC) and the resolution of structural integrity issues identified by the Nuclear Regulatory Commission for Alloy 709. The maximum use temperature of 760°C for the Alloy 709 CC has also drawn interest from molten salt reactor vendors and fluoride-salt-cooled high-temperature reactor developers.

The execution of the Phase I plan was initiated in FY 2016. In collaboration with material vendor G.O. Carlson Inc. of Pennsylvania, the Advanced Reactor Technologies (ART) program successfully scaled up the production of Alloy 709 from a laboratory heat of 500 lb to a commercial heat of 45,000 lb in 2017 (Natesan et al. 2017). A comprehensive creep test matrix has been developed to support the preliminary 100,000 hr, 300,000 hr, and 500,000 hr Alloy 709 CCs. Major testing tasks per ASME Section III, Division 5, Subsection HB, subpart B (ASME 2019a)also include the development of temperature-dependent fatigue design curves and creep-fatigue (CF) damage interaction diagrams. Code Case testing on the Carlson heat Alloy 709 is ongoing at ORNL (Wang et al. 2018, Wang and Sham 2019, Wang et al. 2020a). Completion of the Alloy 709 CC will allow US reactor vendors to decrease capital costs, expand design envelopes, and increase safety margins in the deployment of SFRs and other reactor concepts. Doing so will boost the competitiveness of the US advanced reactor sector, create high-paying jobs, and increase economic growth.

It has been a long-term goal of ASME code committees to develop improved, simplified design rules that are more simply defined, easier to apply, and that take advantage of modern computing capabilities. The use of simplified Elastic-Perfectly Plastic (EPP) analysis methods avoids the complexities and limitations of the traditional ASME linear elastic stress classification design methods, hence greatly simplifying the design evaluation procedure. Currently, EPP-based design methods have been qualified for ASME Section III, Division 5 Class A applications for SS304, SS316 and Grade 91 via two approved Code Cases: strain limits CC (CC N-861) and EPP creep-fatigue (CC N-862) and for Alloy 617 via Code Case N-898. Allowing the use of the simplified EPP methods for the design of Alloy 709 reactor components is a requirement of the Alloy 709.

This report documents the FY 2020 research plans and initiation of testing activities at ORNL in verifying the key assumptions of EPP methods for Alloy 709.

2. MATERIALS

The Alloy 709 plate material used in this study is from Carlson heat Alloy 709 with a heat number of 58776-3RBC. The plate was fabricated through electroslag remelting (ESR), followed by hot rolling and subsequent solution annealing (SA) at 1150°C (ESR 1150). The nominal thickness of the ESR plates was 28.5 mm. The chemical composition of ESR 1150 is listed in Table 1. For comparison, chemical specifications of, TP310MoCbN, with a UNS number of S31025 in ASME SA-213 (ASME 2019b) is also listed in the Table 1. ESR 1150 Alloy 709 in this study met the specified NF709 chemical requirements.

Table 1. Chemical compositions of Alloy 709 ESR 1150 (heat number 58776-3RBC) compared with the chemical requirements of TP310MoCbN (UNS-S31025) (wt %).

Heat or lot ID	C	Cr	Co	Ni	Mn	Mo	N	Si	P	S	Ti	Nb	Al	B	Cu
58776-3RBC	0.066	20.05	0.02	25.14	0.90	1.51	0.152	0.38	0.014	0.001	0.01	0.26	0.02	0.0030	0.06
UNS-S31025	0.10 max	19.0–23.0	–	22.0–28.0	1.50 max	1.0–2.0	0.10–0.25	1.00 max	0.030 max	0.010 max	0.20 max	0.10–0.40	–	0.002–0.010	–

Note: Balance is iron.

For high-temperature components, a material's ability to withstand combined cyclic loading and creep deformation is expected to be a critical aspect of its application. A preliminary study of the CF behavior of Alloy 709 showed significant improvement in the CF life over the as-annealed condition after heat treatment (McMurtrey 2018, Rupp and McMurtrey 2020). The precipitates introduced in the microstructure by heat treatment played an important role in the enhanced CF performance (Zhang, Sham and Young,2019). To achieve combined good creep resistance and CF performance, it was recommended that testing of heat-treated ESR 1150 be included in the CC testing matrix (Wang et al. 2020a). To be consistent, the ESR 1150 plate used in this report went through the same heat treatment procedure prior to specimen machining. The heat treatment was 775°C for 10 hr in air followed by air cooling. All the testing specimens were machined from the mid-thickness of the Alloy 709 plates along the rolling direction.

3. EVALUATION OF THE EFFECT CYCLIC LOADING HISTORY ON CREEP PROPERTIES

3.1 EVALUTION METHOD AND SPECIMEN

Elastic-Perfectly Plastic procedures for cyclic hardening materials and cyclic softening materials were developed in ASME Section III, Division 5, and EPP-based design methods have been qualified for applications for SS316, SS304, Alloy 617, and Grade 91. The approved materials for EPP analysis are categorized as either cyclic hardening material (SS316, SS304 or Alloy 617) or cyclic softening material (Gr.91). The evaluation method used in determining the effect of cyclic softening on the creep behavior of Gr.91 for EPP analysis was documented in Wang et al. (2017) and Messner and Sham (2019). The same evaluation procedure was adopted in this study on Alloy 709. The effect of cyclic loading on creep rate is evaluated by introducing strain-controlled cyclic fatigue segments into a creep test. The changes in the minimum creep rate (MCR) due to cyclic loading history are used to determine reduction factors to be applied to the isochronous curves. These types of tests can establish reduction factors to adjust the existing ASME Code isochronous curves to account for any cyclic softening (see Messner and Sham 2017). Softened isochronous data may be needed to preserve the conservatism of the EPP methods for fatigue-dominated load histories.

The testing procedure is schematically illustrated in Figure 1. The test starts with a load-controlled creep segment that is then unloaded to zero load before switching the test machine to strain control and cycled for a fatigue segment. The sequential creep and fatigue segments are repeatedly applied to the specimen until failure occurs.

To be able to switch between the creep segment and the fatigue segment, the evaluation is performed on a servo-hydraulic machine. The suitable test specimen for this evaluation is the standard CF specimen shown in Figure 2. A photograph of an as-received specimen is shown in Figure 3. A test was designed and initiated at 700°C. The stress level selected for the creep segment was 90 MPa. The fatigue segment had 100 cycles at 1% strain range with a 1E-3 s^{-1} strain rate. The detailed testing parameters are listed below in Table 2.

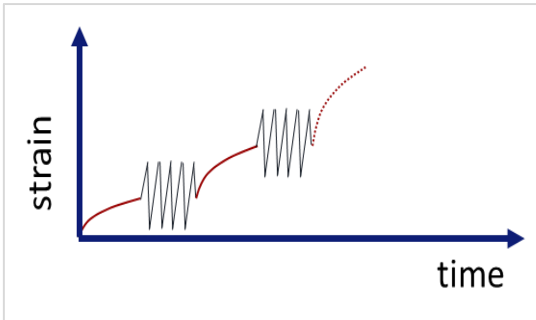


Figure 1. Schematics of the combined creep/fatigue experiments.

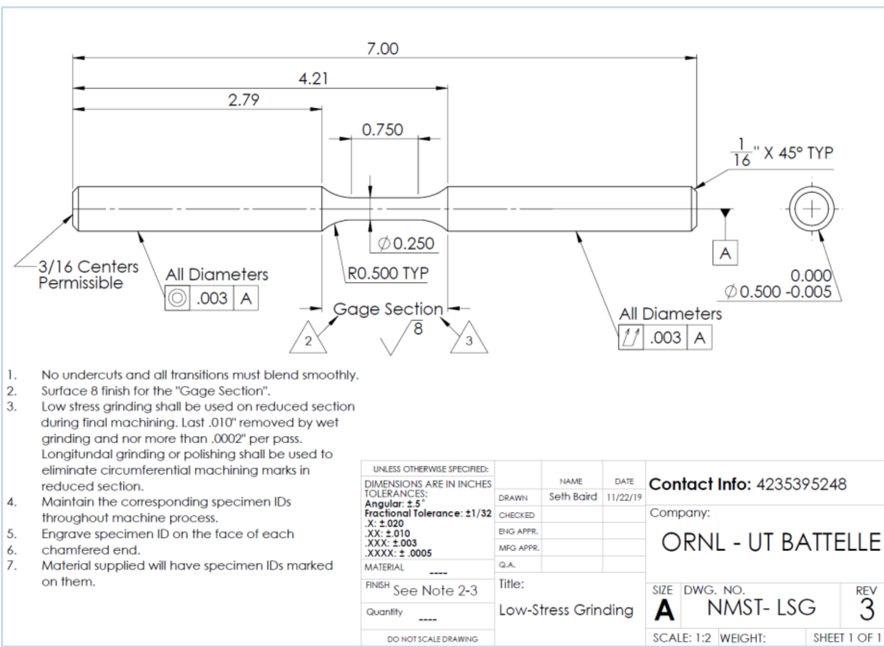


Figure 2. Standard Alloy 709 fatigue specimen geometry. Dimensions are in inches.

Figure 3. Photograph of the as-received Alloy 709 fatigue specimen.

Table 2. Test parameters for combined creep and fatigue experiment on heat-treated ESR 1150 (heat number 58776-3RBC) at 700°C.

Creep segment	Applied stress	90 MPa
	Control mode	Load controlled
	Loading rate	1.5 second to the stress level
	Creep segment duration, hr	>24 hr (i.e., reached steady-state creep)
Fatigue segment	Strain ranges	1%
	Control mode	Strain controlled
	Strain rate	1E-3/s
	Number of cycles of each fatigue segment	100

3.2 PRELIMINARY RESULTS

The specimen tested with combined sequential creep and fatigue at 700°C accumulated a total of five creep segments and four fatigue segments. The preliminary results reported here are from these segments. However, the specimen buckled unexpectedly during the fifth fatigue segment, and therefore, this test did not yield valid failure data.

The preliminary creep test results from five creep segments are summarized in Table 3, and the creep curves are plotted in Figure 4. The duration of each creep segment was at least 25 hr or when steady-state creep was observed. The first creep segment was on a heat-treated specimen, i.e., without any fatigue loading history. The specimen quickly reached a steady-state creep stage after approximately 16 hr. The MCR of the first creep was about 2E-3%/hr. After the first creep segment was completed, the specimen was loaded with 100 fatigue cycles at 1% strain range. The second creep segment was carried out on this specimen at the same stress level of 90 MPa after the 100 fatigue cycles. Noticeable differences in the creep behavior between these first two creep segments included an increase in the primary creep strain and a longer time to reach steady-state creep. For the remaining creep segments, the primary creep strain did not show significant changes, although additional fatigue cycles were applied. The MCR did not show significant differences among all the creep segments. The accumulated strains mainly came from the steady-state creep stage for the first creep segment and the primary creep stage for the remaining creep segments.

Table 3. Summary of the results from the creep segments at 90 MPa and 700°C.

Segment No.	Duration, hr	Time to reach steady-state creep, hr	Primary creep strain, %	Accumulated creep strain, %	Minimum Creep Rate, %/hr
Creep 1	52.7	16.0	0.03	0.10	2.00E-03
Creep 2	70.7	26.3	0.17	0.24	1.10E+03
Creep 3	42.2	24.3	0.23	0.29	1.70E-03
Creep 4	25.9	~20	0.22	0.28	2.70E-03
Creep 5	25.2	~20	0.17	0.19	2.10E-03

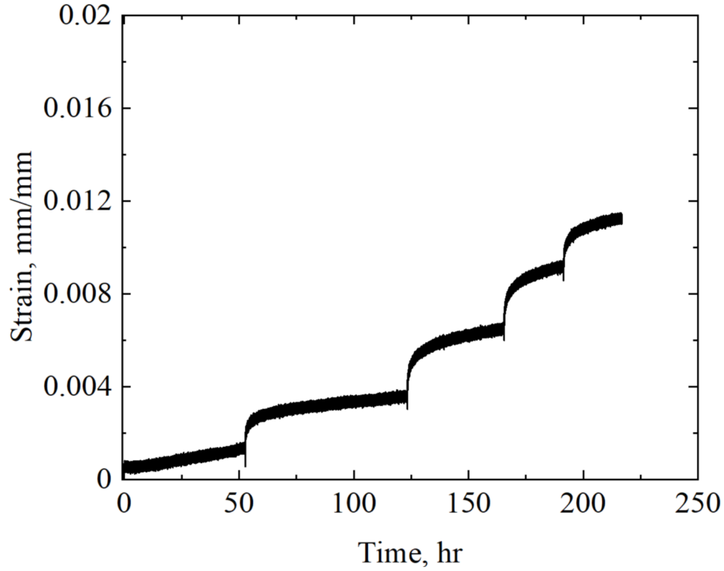


Figure 4. Creep curves of the five creep segments at 700°C.

The reduction factor to account for the cyclic softening effect on creep is determined from changes in the MCR. Based on the preliminary results from this test, the introduction of softening factors to Alloy 709 is not recommended when it is integrated into the EPP analysis. Additional test results are needed to confirm this conclusion.

The peak stresses and the stress ranges as a function of the applied cycles from the four fatigue segments are plotted in Figure 6 and Figure 7. The specimen showed an increase in the peak stresses during the initial 20 cycles followed by approximately constant peak stresses and stress ranges for the remaining cycles in the segment. This fatigue behavior was similar for all the four segments.

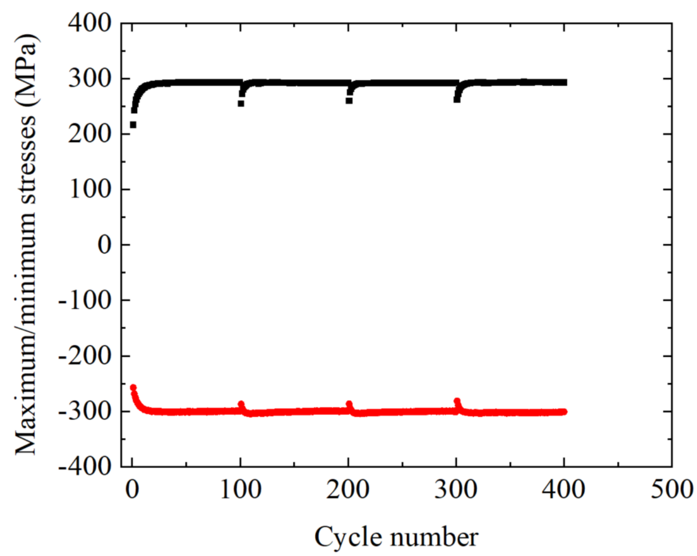
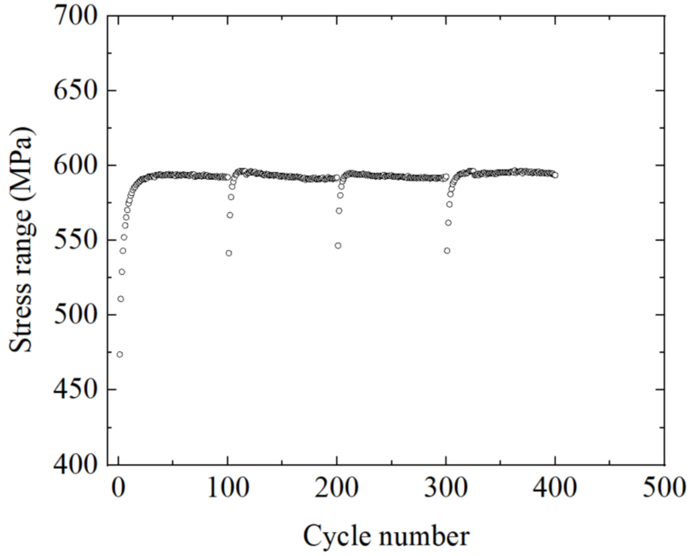


Figure 5. Maximum and mininmum stresses of the fatigue segments at 700º C



(b)

Figure 6. Stress ranges of the fatigue segments at 700º C.

4. DESIGN AND PREPERATION FOR MULTI-AXIAL CREEP TESTING

4.1 TEST DESIGN AND PLAN

Development of the code rules for the primary load check for Alloy 709 is ongoing. Alloy 709 is a known cyclic softening material, and the primary load CC will have to account for its cyclic softening characteristics. The primary load code rules are being developed at Argonne National Laboratory, the idea being to use the EPP method to conduct the global creep rupture check and use the simplified inelastic method (elastic-creep model) to conduct the local creep rupture check. Determining how to treat the local triaxial stress state in the analysis will require experimental validation. Plans are to conduct supporting creep tests on the specimens under various combinations of multi-axial stress states at ORNL and to evaluate the stress measure that provides the best correlations with the creep rupture life of Alloy 709.

A biaxial stress state will be introduced in tubular creep specimens by applying combinations of axial load to internal pressurization. The testing methods and testing plan are similar to what was proposed by Wang et al. (2020b). The stresses introduced by various combinations of the internal pressure and the external axial load, either tensile or compressive, will allow various stress ratios to be developed in the specimen. For example, for the same effective von-Mises stress of 90 MPa (13.1 ksi), Table 4 shows the calculated internal pressure with hoop-to-axial stress ratios of -2 to 2 for a specimen geometry with an internal diameter, *D*, of 0.6 in. and a wall thickness, *t*, of 0.06 in. The axial stress, σ_a, is the sum of the stress introduced by the internal pressure, *p*, for an enclosed tubular specimen and the external axial load, $\sigma_{a.external}$, as

$$\sigma_a = \frac{p*D}{4t} + \sigma_{a.external} \ . \qquad (1)$$

The negative axial stress values in Table 4 require a compressive external axial load, and the positive values require a tensile external axial load.

Table 4. Designed stress state with an effective von-Mises stress of 90 MPa (11.6 ksi).

Ratio of hoop stress to axial stress	Internal pressure, ksi	Hoop stress, ksi	Axial stress, ksi	External axial load, ksi
–2	1.94	9.70	-4.85	-9.70
–1.5	1.78	8.89	-5.93	-10.38
–1	1.50	7.52	-7.52	-11.29
–0.5	0.99	4.97	-9.93	-12.41
0	0.00	0.00	13.05	13.05
0.5	1.43	7.17	14.35	10.76
1	2.37	11.87	11.87	5.93
1.5	2.67	13.36	8.91	2.23
2	2.74	13.68	6.84	0.00

Creep specimens with external axial loading capabilities are designed to perform the multi-axial stress state creep evaluations. The designed specimen geometry for pure internal pressure loading or external compressive axial load is shown in Figure 7 and that for testing with external tensile axial load is shown in Figure 8. Special fixtures are designed for loading specimens in compression in a conventional creep frame. A series of test conditions will be selected, and the target is to produce short-term creep rupture data with multi-axial stress state. It is also planned to implement high temperature strain measurement s to record the axial strain and hoop strain during the creep process.

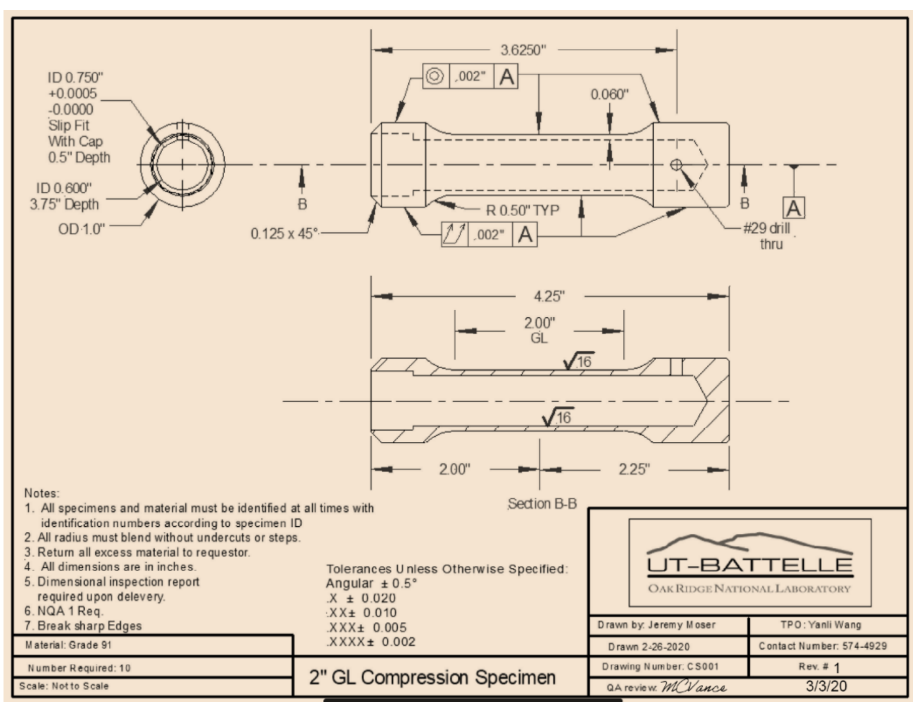


Figure 7. Specimen design for creep testing with internal pressure and external axial compression loading.

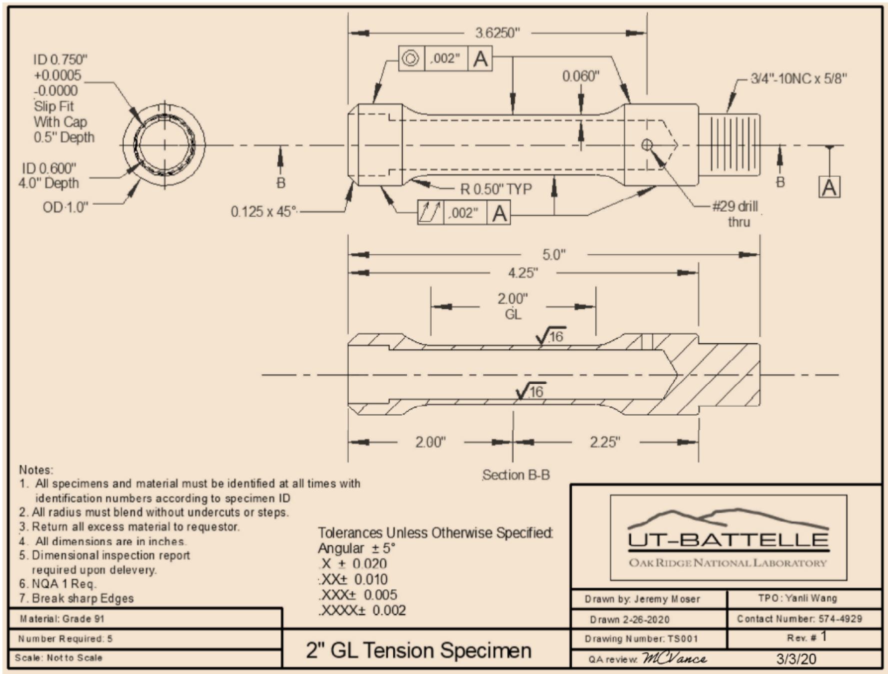


Figure 8. Specimen design for creep testing with internal pressure and external axial tension loading.

At the time of writing this report, the specimens had been machined and the tests were being assembled. Photographs of the specimens machined out of heat-treated Alloy 709 ESR 1500 plate are shown in Figure 8 and Figure 10. The testing will be initiated and continue in FY 2021.

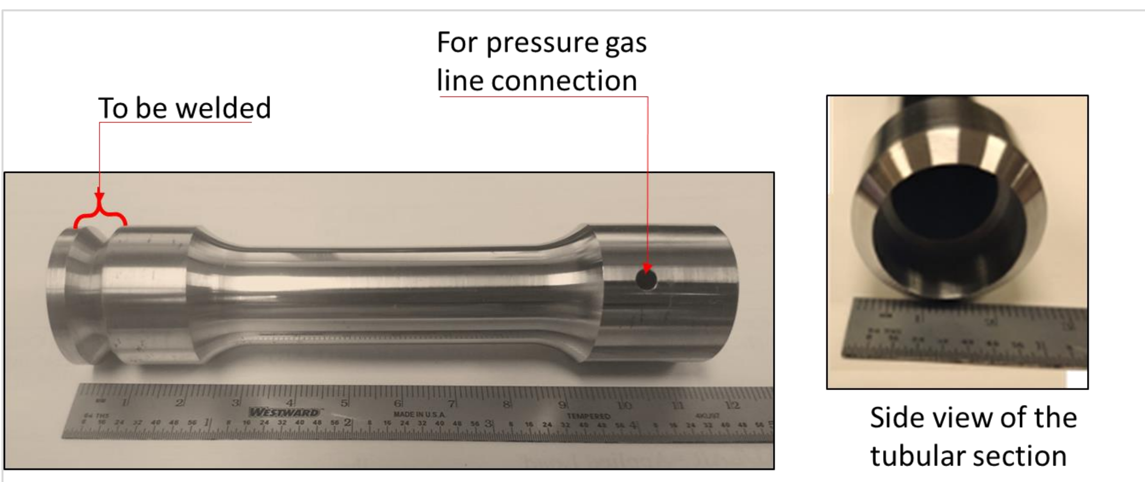


Figure 9. Photographs of a specimen for multi-axial stress creep testing with axial compression.

Figure 10. Photographs of a specimen for multi-axial stress creep testing with axial tension.

5. SUMMARY

The testing plan, experimental design, and the preliminary test results in support of the ASME EPP analysis of Alloy 709 at ORNL in FY 2020 are summarized in this report. The preliminary results show that cyclic loading has an insignificant effect on the MCR; therefore, reduction factors on the isochronous stress-strain curves are not recommended for integrating Alloy 709 in EPP analysis. Additional tests are needed to confirm this preliminary assessment. In addition, the preliminary testing plan for multi-axial creep rupture has been established, and specimens were machined from the heat-treated Alloy 709 ESR 1150 plate. Execution of the multi-axial creep testing matrix will be initiated and carried out in FY 2021.

6. REFERENCES

ASME. 2019a. Boiler and Pressure Vessel Code, Section III Division 5, *Rules for Construction of Nuclear Facility Components*, Subsection HB Subpart B, American Society of Mechanical Engineers, New York, NY (2019 Edition).

ASME SA-213. 2019b. *Standard Specification for Seamless Ferritic and Austenitic Alloy-Steel Boiler, Superheater, and Heat-Exchanger Tubes*, ASME Coiler and Pressure Vessel Code, Section II Materials, American Society of Mechanical Engineers, New York, NY (2019 Edition).

McMurtrey, M. 2018. *Report on the FY18 Creep Rupture and Creep-Fatigue Tests on the First Commercial Heat of Alloy 709*, INL/EXT-18-46140. Idaho Falls, ID: Idaho National Laboratory.

Messner, M. C. and T.-L. Sham. 2017. *FY17 Status Report on the Initial EPP Finite Element Analysis of Grade 91 Steel*, Technical Report No. ANL-ART-94. Chicago, IL: Argonne National Laboratory.

Messner M. C. and T.-L. Sham. 2019. *Draft ASME Section III Division 5 Code Cases to extend EPP strain limits and creep-fatigue design methods to Grade 91*, ANL-ART-165. Lemont, IL: Argonne National Laboratory.

Natesan, K., X. Zhang, T.-L. Sham, and H. Wang. June 2017. *Report on the Completion of the Procurement of the First Heat of Alloy 709*, ANL-ART-89. Lemont, IL: Argonne National Laboratory.

Rupp, R. and M. D. McMurtrey. 2020. *Status of INL Aged A709 Mechanical Testing*, INL/EXT-20-59501. Idaho Falls, ID: Idaho National Laboratory.

Wang, Y., M. C. Messner, and T.-L. Sham. 2017. *FY17 Status Report on Testing Supporting the Inclusion of Grade 91 Steel as an Acceptable Material for Application of the EPP Methodology*, ORNL/TM-2017/388. Oak Ridge, TN: Oak Ridge National Laboratory.

Wang, H., C. S. Hawkins, E. C. Disney, and J. L. Moser. 2018. *The Initiation of Long-Term Creep Rupture Tests on the First Alloy 709 Commercial Heat*, ORNL/TM-2018/985. Oak Ridge, TN: Oak Ridge National Laboratory.

Wang, Y. and T.-L. Sham. 2019. *Planned FY19 Creep and Fatigue Design Curve Testing of Alloy 709 Base Metal*, ORNL/TM-2019/1303. Oak Ridge, TN: Oak Ridge National Laboratory.

Wang, Y., P. Hou, and T.-L. Sham. 2020a. *Report on FY 2020 Creep, Fatigue, and Creep-Fatigue Testing of Alloy 709 Base Metal at ORNL*, ORNL/TM-2020/1622. Oak Ridge, TN: Oak Ridge National Laboratory.

Wang, Y., P. Hou, R. I. Jetter, and T.-L. Sham. 2020b. *Report on FY 2020 Testing in Support of the Development and Extension of ASME Code Rules for Grade 91*, ORNL/TM-2020/1613. Oak Ridge, TN: Oak Ridge National Laboratory.

Zhang, Z., T.-L. Sham and G. A. Young. 2019. *Microstructural Characterization of Alloy 709 Plate Materials with Additional Heat Treatment Protocol*, ANL-ART-170. Lemont, IL: Argonne National Laboratory.