ORNL/TM-2019/1303

Planned FY19 Creep and Fatigue Design Curve Testing of Alloy 709 Base Metal

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Materials Science and Technology Division

PLANNED FY19 CREEP AND FATIGUE DESIGN CURVE TESTING OF ALLOY 709 BASE METAL

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ABBREVIATIONS, ACRONYMS, AND INITIALISMS

AOD	argon-oxygen-decarburization
ART	Advanced Reactor Technologies
ANL	Argonne National Laboratory
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
DOE	Department of Energy
EL	elongation
ESR	electroslag remelt
INL	Idaho National Laboratory
LVDT	Linear variable differential transformer
MCR	minimum creep rate
NE	Office of Nuclear Energy
ORNL	Oak Ridge National Laboratory
S/A	solution annealing
RA	reduction of area
TC	thermocouple

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ABSTRACT

This report summarizes the status of planned FY 2019 creep and fatigue testing of the first commercial heat of Alloy 709 base metal at Oak Ridge National Laboratory (ORNL).

A comprehensive master creep testing matrix was generated to support the ASME code qualification of Alloy 709. The testing activities and research are carried out at Argonne National Laboratory, Idaho National Laboratory and ORNL. ORNL was tasked to carry out a subset of the creep Code Case testing matrix for electroslag remelt (ESR) with solution annealing (S/A) at 1100°C in FY 2019. In this reporting cycle, 25 creep tests were started and 9 of them produced rupture data. The remaining 16 tests of ESR with S/A at 1100°C, along with 6 long-term creep tests of argon-oxygen-decarburization with S/A at 1100°C, are ongoing.

A preliminary plan for fatigue testing was formulated. Specimens were machined from ESR with S/A at 1100°C and testing was initiated at 760°C.

This report fulfills the level 3 deliverable for milestone M3AT-19OR020502061, under work package AT-19OR02050206 “A709 Code Case Testing—ORNL.”

1. INTRODUCTION

Because of the significant enhancement in mechanical properties of the austenitic stainless steel Alloy 709 relative to 316H stainless steel, which is a reference construction material for sodium fast reactor systems, code qualification of Alloy 709 was recommended in FY 2014. A comprehensive plan for the development of a 500,000 h, 760ºC ASME Code Case and the resolution of structural integrity issues identified by the Nuclear Regulatory Commission (NRC) for Alloy 709 was developed in FY 2015. The maximum use temperature of 760°C also draws interest from molten salt reactor vendors in the potential use of Alloy 709 in their designs.

The execution of the Phase I plan was initiated in FY 2016. Creep testing frames at Argonne National Laboratory (ANL), Idaho National Laboratory (INL) and Oak Ridge National Laboratory (ORNL) underwent upgrading and refurbishment to support the generation of creep rupture data for the Alloy 709 Code Case. In collaboration with material vendor G.O. Carlson Inc. of Pennsylvania, the Advanced Reactor Technologies (ART) program successfully scaled the production of Alloy 709 from a laboratory heat of 500 lb to a commercial heat of 45,000 lb. The master heat of Alloy 709, heat number 58776, was processed under various processing conditions: argon-oxygen-decarburization (AOD), electroslag remelting (ESR), ESR with subsequent homogenization (ESR-homogenized), and three different solution annealing (S/A) temperatures. The fabrication procedures for the first commercial heat of Alloy 709 hot-rolled plates are summarized in Natesan et al. 2017.

The Alloy 709 plates produced under these different processing conditions were tested for creep, fatigue, and creep-fatigue under selected conditions to screen for the preferred processing condition. Both AOD with S/A at 1100°C and ESR with S/A at 1100°C showed good microstructure and combined high-temperature mechanical properties (McMurtrey 2018). In FY 2018, long-term creep tests were initiated at ORNL for plates produced by AOD with S/A at 1100°C under six different test conditions, at temperatures of 550 to 800°C and stresses of 38 to 309 MPa, to a target rupture time of 60,000 h. This activity is documented in Wang et al. 2018.

The test effort for the comprehensive creep test matrix developed to support the preliminary, 100,000 hr, 3000,000 hr and 500,000 hr Alloy 709 Code Cases was split among ANL, INL and ORNL. ESR with S/A 1100 ºC was added to the intermediate and long-term testing effort in FY 2019. This report documents the status of the planned FY 2019 creep testing and the initiation of fatigue design curve testing on ESR base metal with S/A at 1100°C at ORNL.

2. MATERIALS AND SPECIMENS

The Alloy 709 plates produced by AOD had a subheat number of #58776-4 and those with S/A at 1100°C had a lot ID of #58776-4B. The ESR and ESR-homogenized plates had a subheat number of #58776-3R, and ESR plates with S/A at 1100°C had a lot ID of #58776-3RBB. The chemical compositions of the AOD and ESR with S/A at 1100°C are listed in Table 1.

The creep specimen was designed to have 0.375 in gage diameter with a nominal gage length of 1.875 in. A drawing of the creep specimen is shown in Fig. 1. The standard fatigue specimen had a 0.25 in gage diameter and a 0.75 in gage length (Fig. 2).

Table 1. Chemical compositions of Alloy 709 (wt %).

Heat No.	C	Cr	Co	Ni	Mn	Mo	N	Si	P	S	Ti	Nb	Al	B	Cu
#58776-4B	0.07	19.93	0.02	24.98	0.91	1.51	0.148	0.44	0.014	<.000	0.04	0.26	0.02	0.0045	0.06
#58776-3RBB	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

Balance is Fe.

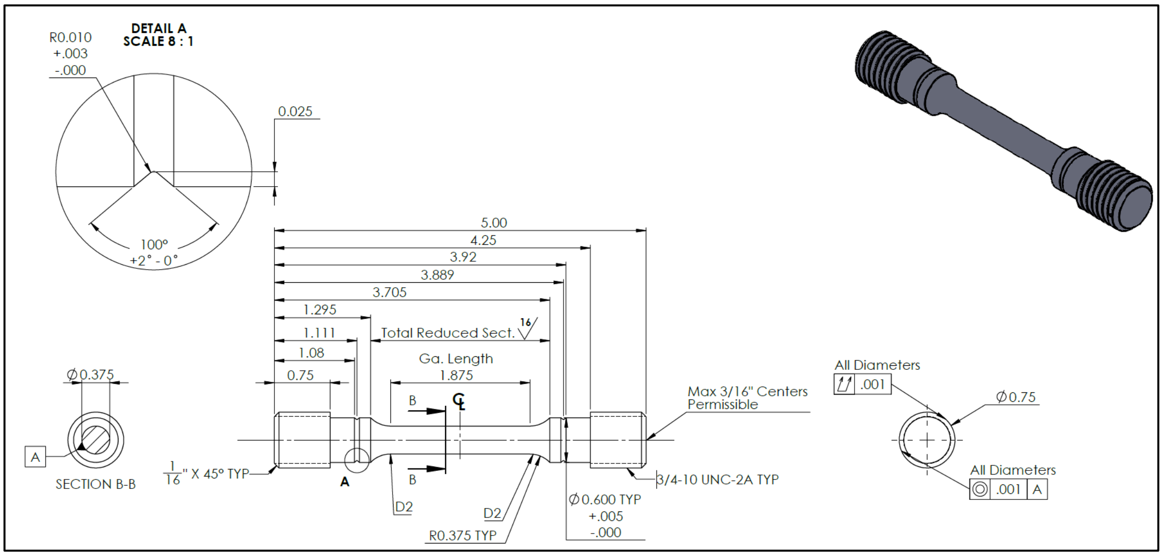

Fig. 1. Creep specimen geometry for Alloy 709 Code Case testing at ORNL. Units are in inches.

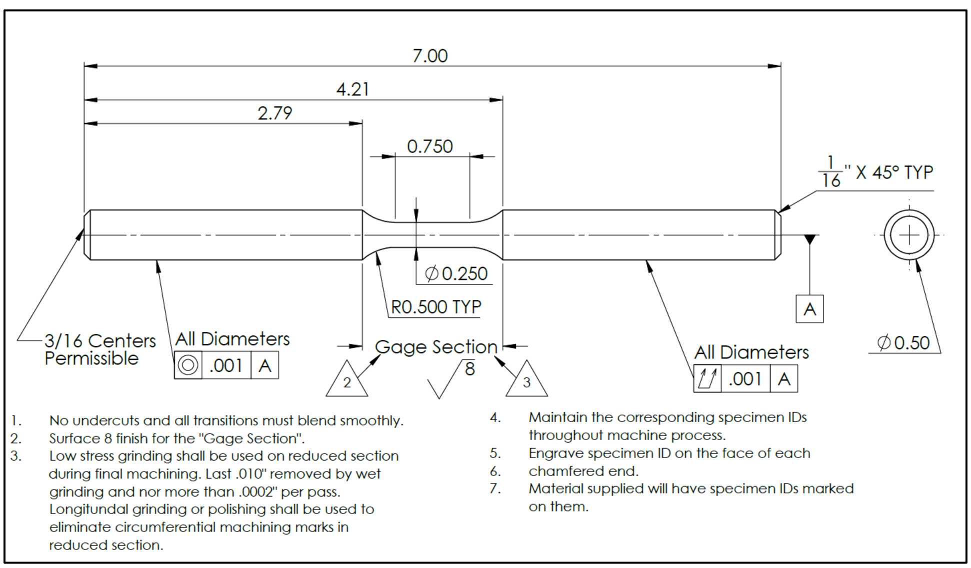

Fig. 2. Standard creep-fatigue specimen geometry. Units are in inches.

3. ALLOY 709 CREEP CODE CASE TESTING

3.1 ORNL ALLOY 709 CREEP CODE CASE TESTING PLAN AND STATUS

A comprehensive master creep testing matrix for Alloy 709 Code Case testing was generated which involved a total of 68 creep tests of ESR with S/A at 1100°C. The testing activities and research to support the qualification of the Alloy 709 are carried out at ANL, INL, and ORNL. The creep testing matrix is to generate data for preliminary, 100,000 h, 300,000 h, and 500,000 h Code Cases. The creep Code Case testing matrix is summarized in Table 2. The creep testing covers a temperature range of 525–950°C and stress levels of 15–380 MPa.

Table 2. Summary of the Alloy 709 creep Code Case testing matrix.

Target Code Case	Predicted life, (h)	Temp. (°C)	Stress, MPa	Labs involved	Planned no. of tests
Preliminary	500 – 10,000	575 – 950	21 – 355	Argonne/INL/ ORNL	36
100,000 h	11,000 – 24,000	550 – 950	15 – 380	Argonne/INL	16
300,000 h	25,000 – 68,000	550 – 925	15 – 330	ORNL	11
500,000 h	91,000 – 109,000	525 – 800	35 – 355	ORNL	5

ORNL was tasked to carry out a subset of the creep Code Case testing matrix of ESR with S/A at 1100°C in FY 2019. The test parameters and status of the 29 creep tests are summarized in Table 3. A picture of one of the as-received creep specimens is shown in Fig. 3.

Fig. 3. As-received Alloy 709 creep specimen.

The testing procedure followed ASTM E 139-11, *Standard Test Methods for Conducting Creep, Creep-Rupture, and Stress-Rupture Tests of Metallic Materials*. The creep tests were arranged to best utilize the individual creep machine capacity and estimated testing time. A major effort was required for calibration of the machines, setting up the tests, and loading the specimens to the test frame. Creep tests began for 25 specimens, and 9 of them had ruptured at the time of this report. The remaining four tests were delayed by specimen machining and will be carried out when additional creep specimens are machined and delivered.

The six long-term creep tests initiated in FY 2018 are listed in Table 4. The details of these tests are documented in Wang et al. 2018. These tests are ongoing, with accumulated creep time of approximately 8,000 h for each test as of September 1, 2019.

Table 3. Creep tests and status of Alloy 709 ESR with S/A at 1100°C at ORNL.

Test number (TN)	Creep frame	Stress, MPa	Temperature, °C	TC type	status
34162	5	355	525	K	Ongoing
34163	6	330	550	K	Ongoing
34182	516	285	550	K	Ongoing
34183	517	285	575	K	Ongoing
34130	94	200	600	K	Ongoing
34110	307	175	625	K	Ongoing
34113	306	155	625	K	Ongoing
34111	305	90	700	K	Ongoing
34161	301	80	700	K	Ongoing
34112	304	80	725	K	Ongoing
34133	78	80	775	K	**Ruptured**
34132	80	80	800	S	**Ruptured**
34184	518	60	750	K	Ongoing
34131	81	60	825	S	**Ruptured**
34160	64	50	850	K	**Ruptured**
34242	511	40	800	K	Ongoing
34181	510	40	875	K	**Ruptured**
34265	64	35	800	K	Ongoing
TBD	TBD	35	825	TBD	To be tested
34244	80	35	875	S	**Ruptured**
34278	83	35	900	S	**Ruptured**
34277	79	35	925	S	**Ruptured**
34242	81	27	925	S	**Ruptured**
34274	76	21	875	S	Ongoing
34275	77	15	925	S	Ongoing
34245	89	50	825	K	Ongoing
TBD	TBD	40	850	TBD	To be tested
TBD	TBD	27	900	TBD	To be tested
TBD	TBD	21	925	TBD	To be tested

* TBD: to be determined.

Table 4. Creep tests and status of Alloy 709 AOD with S/A at 1100°C at ORNL.

Test number	Creep frame	Stress, MPa	Temperature, °C	Status
33629	88	309	550	Ongoing
33630	93	204	600	Ongoing
33631	91	134	650	Ongoing
33632	95	88	700	Ongoing
33635	302	38	800	Ongoing
33636	303	58	750	Ongoing

3.2 SUMMARY OF THE CREEP RUPTURE TESTS OF ESR WITH S/A AT 1100°C

Nine short-term creep rupture test data sets were obtained during this reporting period. The testing results—rupture time, measured elongation (EL), reduction of area (RA), and minimum creep rate (MCR)—are summarized in Fig. 4. The creep curves for the nine ruptured specimens are presented in Fig. 5 and photographs of the ruptured specimens are shown in Fig. 6. All nine tests showed good creep ductility with elongation between 35.7 and 80.3% and RA between 65.5 and 81.5%.

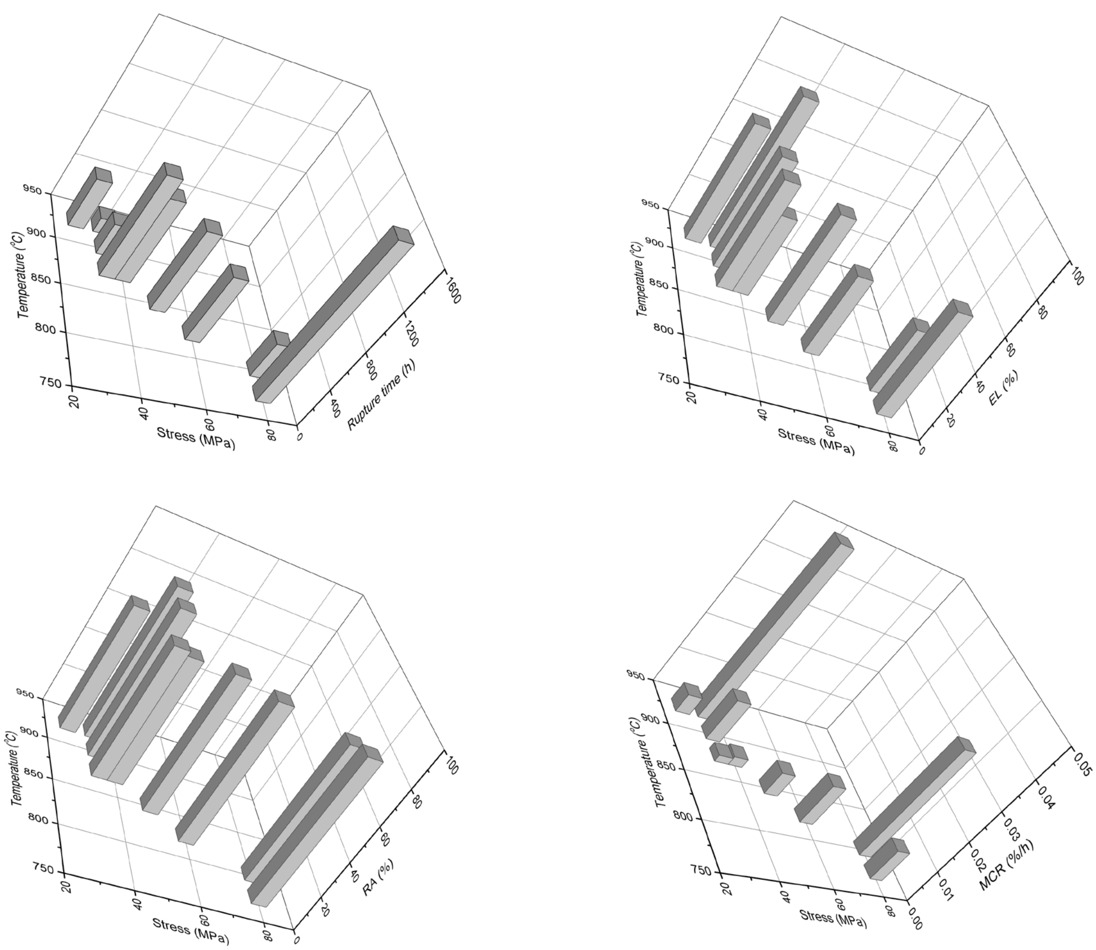

Fig. 4. Summary of the creep rupture test results on ESR with S/A at 1100°C

Due to the large elongation for these tests, the strain signals from the Linear Variable Differential Transformers (LVDTs) ran out of range before the rupture. The LVDTs were reset during the test to continue to capture creep deformation. During the adjustment of the LVDTs, the creep tests were not interrupted, but the strains may have interruptions (shown as the gaps in the creep curve plots), depending on the timing of the LVDT reset process. In some cases, during the tertiary creep stage, the LVDT missed the data points close to rupture, the post-test measurements are used as the total creep strain (shown as the last single data point on the creep curve plots).

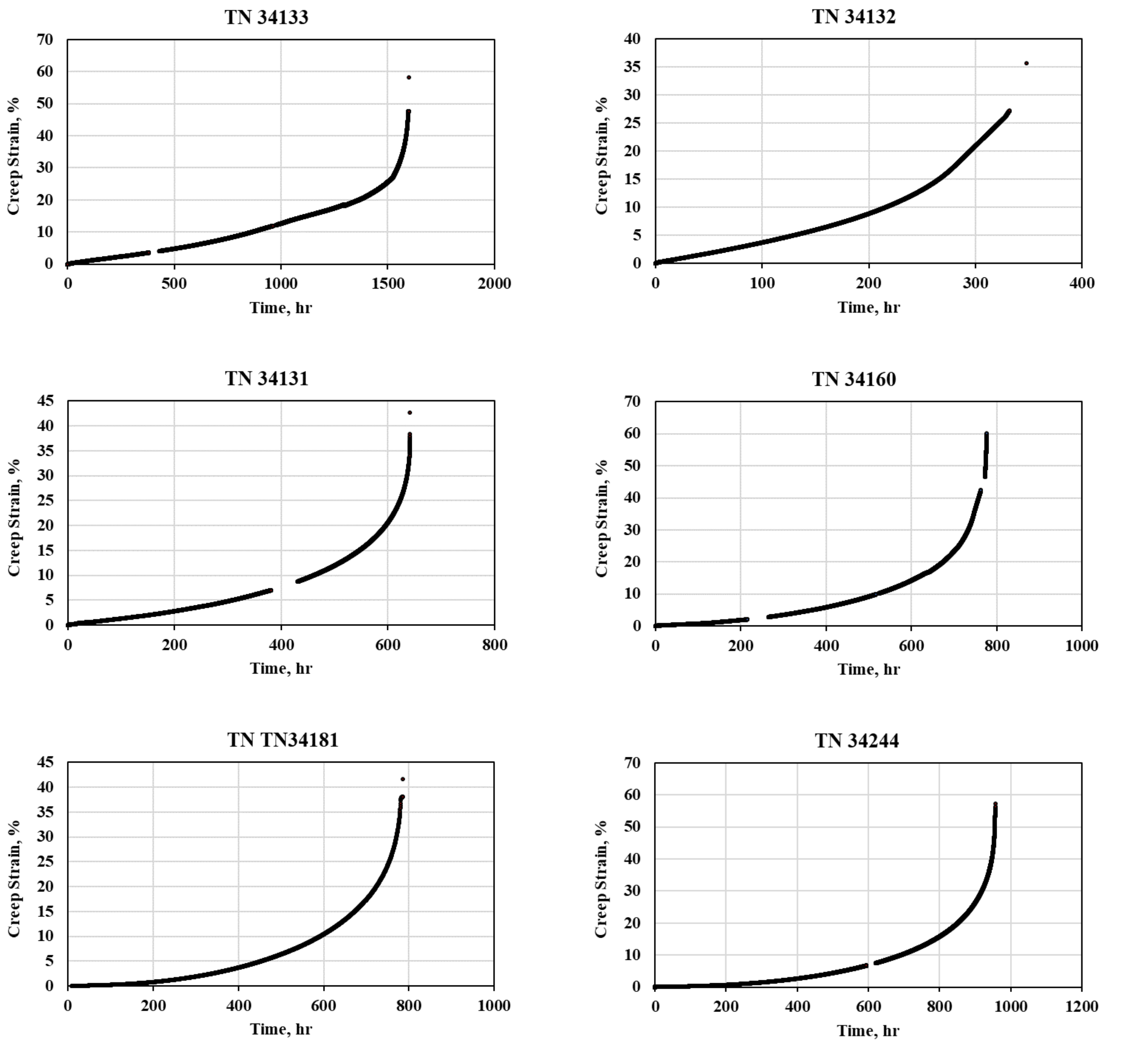

Fig. 5. Creep curves of the ruptured ESR with S/A at 1100°C.

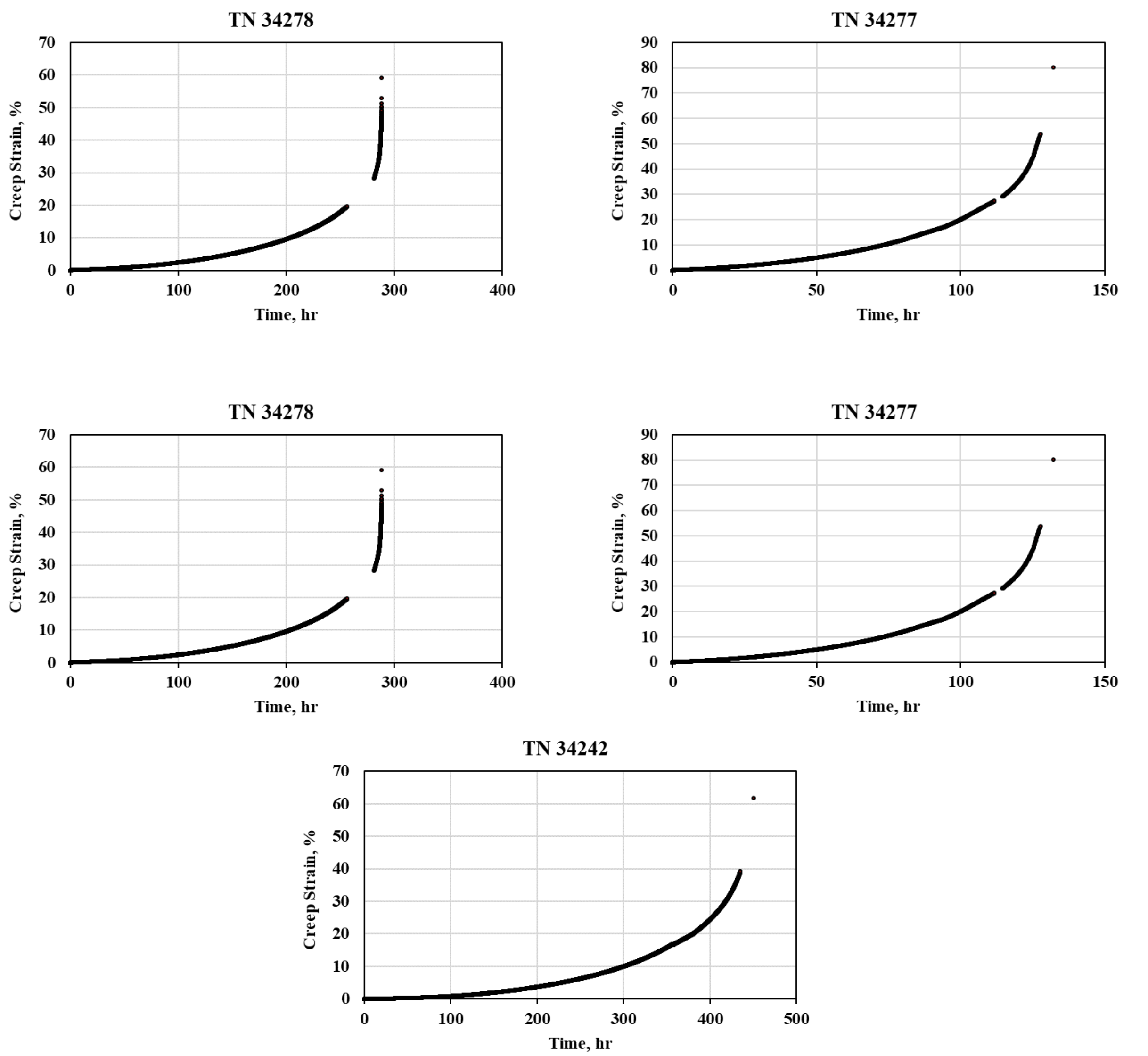

Fig. 5. Creep curves of the ruptured ESR with S/A at 1100 °C (continued).

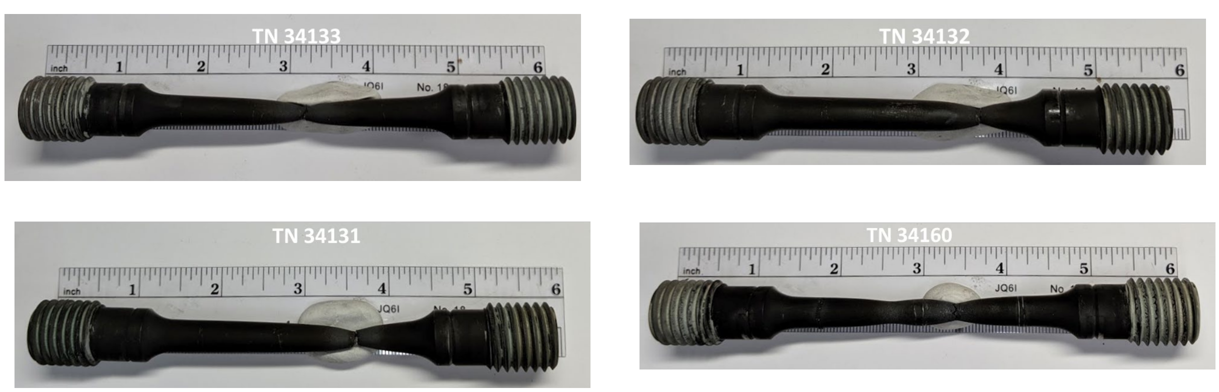

Fig. 6. Photographs of the ruptured creep specimens of ESR with S/A at 1100°C.

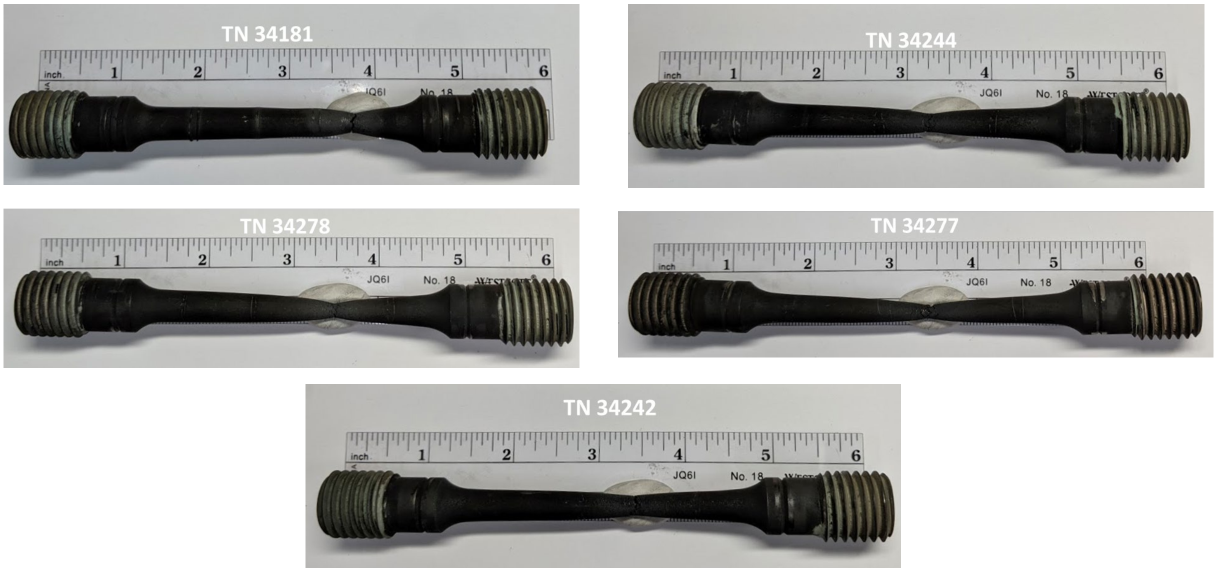

Fig. 6. Photographs of the ruptured creep specimens of ESR with S/A at 1100 ºC (continued).

4. INITIATION OF FATIGUE TESTING ON ALLOY 709

4.1 PRELIMINARY FATIGUE TESTING PLAN

A preliminary testing plan for development of Alloy 709 fatigue design curves has been generated to cover temperatures of 500, 500, 550, 650 and 760°C and strain range from 3% to 0.2%. this plan is summarized in Table 5. Testing will follow a strain-controlled fatigue standard (i.e., ASTM E606). The strain rate will be controlled at 1E-3 s^{-1}. The loading is a triangular shape with a fully reversed profile, i.e., a loading ratio of R = –1 (schematically shown in Fig. 7). Two or three duplicate tests are planned. It is expected that the testing at the low strain range of 0.2% will result in a large number of cycles and hence a long test duration; only two duplicates are planned at this strain range.

Table 5. Summary of the preliminary fatigue testing plan for Alloy 709.

Material	Temperatures, °C	Strain range, %	Strain rate, s^{-1}	R ratio	Duplicate
ESR with S/A at 1100°C	500, 550, 650, 760	3, 2, 1, 0.6, 0.4, 0.3, 0.2	1E-3	–1	2–3

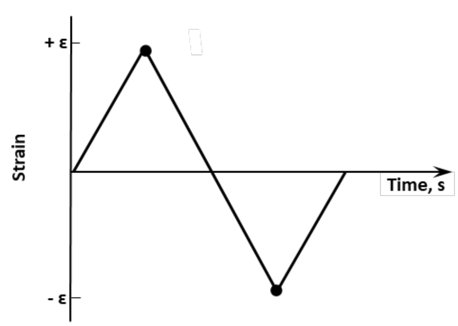

Fig. 7. Strain-controlled fatigue loading profile for one cycle.

The specimen design used a standard fatigue specimen per ASTM E606. A photo of the as-received fatigue specimen machined from ESR with S/A at 1100°C is shown in Fig. 8.

Fig. 8. As-received Alloy 709 fatigue specimen.

4.2 PRELIMINARY FATIGUE TESTING RESULTS AT 760°C

The fatigue testing of specimens from ESR plates with S/A at 1100°C was initiated at 760°C in FY 2019. Six tests were completed at strain ranges of 1%, 0.6%, 0.4%, and 0.3%. The maximum and minimum stresses as a function of the applied cycles are plotted in Fig. 9. Two fatigue tests were performed at the 1% and 0.6% strain ranges, and the results were consistent between the two duplicates for both strain ranges.

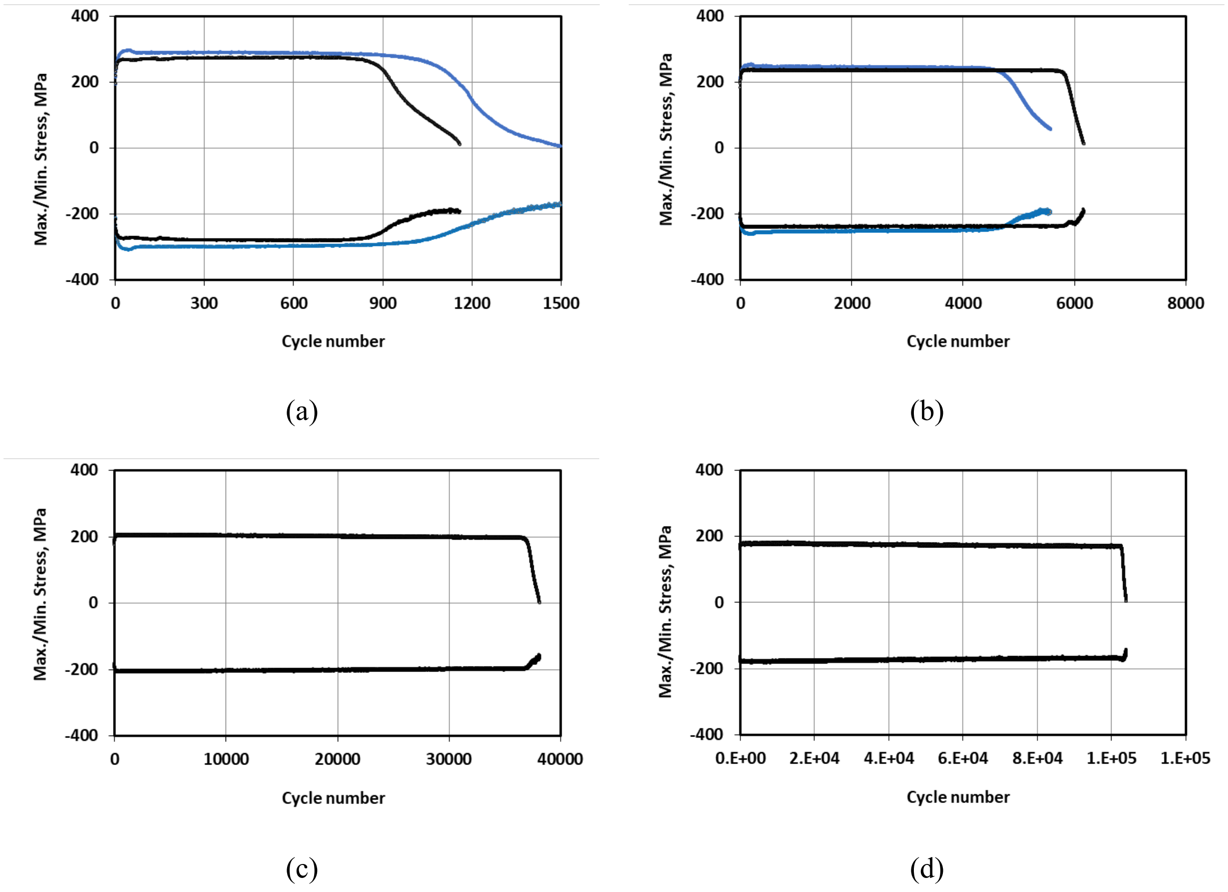

Fig. 9. Maximum and minimum stresses of fatigue tests on ESR specimens with S/A at 1100°C at 760°C at strain ranges of 1% (a), 0.6% (b), 0.4% (c), and 0.3% (d). The black and blue lines in (a) and (b) are duplicate tests of the same conditions.

All the fatigue tests at 760°C showed small cyclic hardening at the very beginning of the cycles. The maximum and minimum stresses showed insignificant cyclic hardening after the initial cycles.

The test specimens failed inside the gage length. A typical fatigue specimen after testing is pictured in Fig. 10.

Fig. 10. An Alloy 709 fatigue specimen after testing.

The cycles to failure for the six fatigue tests are summarized in Table 6. The criteria used for determining the cycles to failure were based on a 20% maximum load drop.

Table 6. Fatigue test results of ESR with S/A at 1100°C at 760°C.

Test number	Specimen ID	Strain range, %	Cycles to failure*
34339	3RBB1_4_C1-01	1%	1,125
34464	3RBB1_4_C1-03	1	918
34371	3RBB1_4_C1-02	0.6	4,920
34473	3RBB1_4_C1-04	0.6	5,903
34492	3RBB1_4_C1-05	0.4	37,320
34523	3RBB1_4_C1-06	0.3	103,310
34574	*3RBB1_4_C1-07*	*0.2*	*Ongoing*

*Failure criteria: 20% maximum load drop

5. SUMMARY

The planned FY 2019 creep testing at ORNL in support of the ASME code qualification of Alloy 709 is summarized in this report. Creep tests were started for 25 ESR with S/A at 1100°C base metal specimens, for which 9 short-term creep rupture data sets were generated in this reporting cycle. The remaining 16 tests of ESR specimens with S/A at 1100°C, along with the 6 long-term creep tests of AOD with S/A at 1100°C, are ongoing.

A preliminary plan for fatigue testing was formulated for Alloy 709. Fatigue testing was initiated at 760°C on specimens machined from ESR with S/A at 1100°C. The preliminary fatigue test results at strain ranges of 1, 0.6, 0.4, and 0.3% are summarized in this report.

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