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Report on FY 2021 Creep, Fatigue, and Creep-Fatigue Testing of Alloy 709 Base Metal at ORNL

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August 2021

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OAK RIDGE NATIONAL LABORATORY
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Materials Science and Technology Division

REPORT ON FY 2021 CREEP, FATIGUE, AND CREEP-FATIGUE TESTING OF ALLOY 709 BASE METAL AT ORNL

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ABBREVIATIONS, ACRONYMS, AND INITIALISMS

ANL	Argonne National Laboratory
AOD	argon-oxygen-decarburization
ART	Advanced Reactor Technologies
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
CF	creep-fatigue
DOE	Department of Energy
ESR	electroslag remelt
INL	Idaho National Laboratory
LMP	Larson-Miller Parameter
NE	Office of Nuclear Energy
ORNL	Oak Ridge National Laboratory
SA	solution-annealing or solution-annealed
SFR	sodium fast reactor

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ABSTRACT

The testing activities and research in support of ASME Code qualification of Alloy 709, an advanced austenitic steel, are being carried out at Oak Ridge National Laboratory (ORNL), Argonne National Laboratory, and Idaho National Laboratory. ORNL has been tasked to carry out a subset of the Code Case testing for creep rupture, fatigue and creep-fatigue.

The focus of the FY 2021 Code Case testing on Alloy 709 base metal at ORNL includes (1) continuing the long-term creep rupture testing on ESR1100 and AOD1100; (2) adding ESR1150-AH to the creep Code Case testing matrix; and (3) continuing fatigue and creep-fatigue Code Case testing on ESR1150-AH. This report summarizes the status and the preliminary test results of FY 2021 planned Code Case testing at ORNL.

1. INTRODUCTION

Nuclear power contributes significantly to meeting US 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, there must be improvements in its capital cost and economic return before the private sector invests in large-scale, commercial deployment of SFRs. Advanced materials can have a significant impact on the flexibility, safety, and economics of future SFRs because innovative designs and design simplifications could be possible using materials with enhanced mechanical properties. Improved materials performance also impacts safety through improved reliability and greater design margins, and improved material reliability could result in reduced downtime. The objective of the Advanced Materials Development activities of the Advanced Reactor Technologies (ART) Program for the US Department of Energy, Office of Nuclear Energy is to provide the technical basis needed to support the regulatory requirements for structural materials for advanced reactors that could be deployed in the near-term to mid-term by the US nuclear industry.

Because of significant enhancements in the 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 in FY 2014. A comprehensive plan was established in FY 2015 for the development of a 500,000 h, 760°C ASME Code Case and the resolution of structural integrity issues identified by the Nuclear Regulatory Commission. The maximum use temperature of 760°C for the Alloy 709 Code Case has also drawn interest from molten salt reactor vendors and fluoride salt-cooled high-temperature reactor developers. Completion of the Alloy 709 Code Case 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.

The data package for code qualification must contain a minimum of three commercial heats which represent the anticipated compositional ranges. In FY 2017, in collaboration with material vendor G.O. Carlson Inc. of Pennsylvania, the 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. The master heat of Alloy 709, heat number 58776, was processed, hot-rolled into plates, and solution-annealed (SA). The fabrication procedures and room-temperature characterization of heat 58776 Alloy 709 plates are summarized in Natesan et al. (2017). Meanwhile, creep-testing frames at Oak Ridge National Laboratory (ORNL) were upgraded or refurbished, and some new creep frames were procured at the Idaho National Laboratory (INL) and the Argonne National Laboratory (ANL), to support the generation of creep rupture data for the Alloy 709 Code Case. The Code Case test effort for the comprehensive creep test matrix developed to support the preliminary, 100,000 h, 300,000 h, and 500,000 h Alloy 709 Code Cases was split among Argonne, INL, and ORNL. In FY 2018, long-term creep tests were initiated at ORNL for plates produced by argon-oxygen-decarburization (AOD) and SA at 1100°C (Wang et al. 2018). In FY 2019, electroslag remelted (ESR) with SA at 1100°C was added to the intermediate and long-term testing effort (Wang and Sham 2019).

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. Zhang, Sham and Young (2019) have developed a heat treatment protocol consisting of 775°C for 10 h applied to as-annealed Alloy 709 to enhance its creep-fatigue resistance. Fatigue and creep-fatigue (CF) testing by McMurtrey and Rupp (2019) showed significant improvement in the CF life of the heat-treated Alloy 709 over that in the as-annealed condition. The precipitates introduced in the microstructure by heat treatment played an important role in the enhanced CF performance (Zhang and Sham 2019). To achieve a balanced creep and

CF performance, heat-treated ESR with SA at 1150°C was added to the Code Case test matrix in FY 2020.

In FY 2021, researchers at INL led the effort in procuring the second commercial heat of Alloy 709 from Allegheny Technologies Incorporated (ATI). Flat rolled plates with the master heat number of 529900 and total weight of 40,500 lb were successfully delivered. At the time of writing of this report, ORNL is in the process of sectioning these plates to support baseline characterization and Code Case testing at the three labs. Meanwhile, two servo-hydraulic machines are being upgraded to add to the high-temperature testing capability in support of CF code case testing with long hold times at ORNL.

This report documents the status and results of the planned FY 2021 creep, fatigue, and CF Code Case testing on Alloy 709 base metal (heat number 58776) at ORNL.

2. MATERIALS

The chemical compositions of Alloy 709 with the heat number 58776 are listed in Table 1. The ESR plates had a sub-heat number of 58776-3R; the plates with SA at 1100°C (ESR1100) had a lot ID of 58776-3RBB, and those with SA at 1150°C (ESR1150) had a lot ID of 58776-3RBC. The nominal thickness of the ESR plates was 28.5 mm. The Alloy 709 plates produced by AOD had a sub-heat number of 58776-4 and those with SA at 1100°C (AOD1100) had a lot ID of 58776-4B. The nominal thickness of the AOD plates was 30 mm.

For comparison, the specifications for the chemical requirements of Nippon Steel NF709, TP310MoCbN, seamless tubing, with a UNS number of S31025 in ASME SA-213 (ASME 2019a) are also listed in Table 1. Alloy 709 with heat number 58776 in this study met the specified NF709 chemical requirements.

An additional heat treatment of the ESR plate with SA at 1150°C was performed to ensure a balanced creep and CF performance. The heat treatment was at 775°C for 10 h in air, followed by air cooling. The heat-treated ESR1150 plates are designated as “ESR1150-AH” in this report.

Table 1. Chemical compositions of Alloy 709 with master heat number 58776 (wt %).

Heat or lot ID	C	Cr	Co	Ni	Mn	Mo	N	Si	P	S	Ti	Nb	Al	B	Cu
58776-3RBB; or 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
58776-4B	0.07	19.93	0.02	24.98	0.91	1.51	0.148	0.44	0.014	<.001	0.04	0.26	0.02	0.0045	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:

1. Balance is iron.
2. 58776-3RBB is Alloy 709 ESR with SA at 1100°C (ESR1100), and 58776-3RBC is Alloy 709 ESR with SA at 1150°C (ESR1150).
3. 58776-4B is Alloy 709 AOD with SA at 1100°C (AOD1100).

3. ALLOY 709 CREEP CODE CASE TESTING

3.1 ALLOY 709 CREEP CODE CASE TESTING PLAN AND STATUS AT ORNL

A comprehensive master creep testing matrix for Alloy 709 Code Case testing to support the qualification of Alloy 709 is being carried out at ANL, INL, and ORNL. A staged approach to qualify A709 will be used to incrementally increase the design-life from 100,000 h to 300,000 h and finally 500,000 h through a series of Code Cases.

The creep Code Case testing matrix is closely monitored. The matrix is revised as needed when new information from ruptured tests becomes available. Table 2 summarizes the creep Code Case testing matrix, which covers a temperature range of 525–1000°C and stress levels of 7–380 MPa.

ORNL has been tasked to carry out a subset of the creep Code Case testing matrix. The testing procedure followed ASTM E 139-11, *Standard Test Methods for Conducting Creep, Creep-Rupture, and Stress-Rupture Tests of Metallic Materials* (ASTM 2011). The creep tests were arranged to best utilize the individual creep machine capacity and estimated testing duration. The specimen geometries for creep Code Case testing are shown in Fig. 1. The creep specimen was designed to have a 9.53 mm gage diameter with a nominal gage length of 47.63 mm. Note that this specimen's gage diameter is larger than the conventional 6.35 mm diameter creep specimen with the purpose of reducing the oxidation effect by decreasing the surface-to-volume ratio using a larger diameter specimen, to support the very long-term testing. Such specimen design is now used even for short term and intermediate term testing for consistency. All the Code Case testing specimens were machined from the mid-thickness of the Alloy 709 plates along the rolling direction, per ASME test practice.

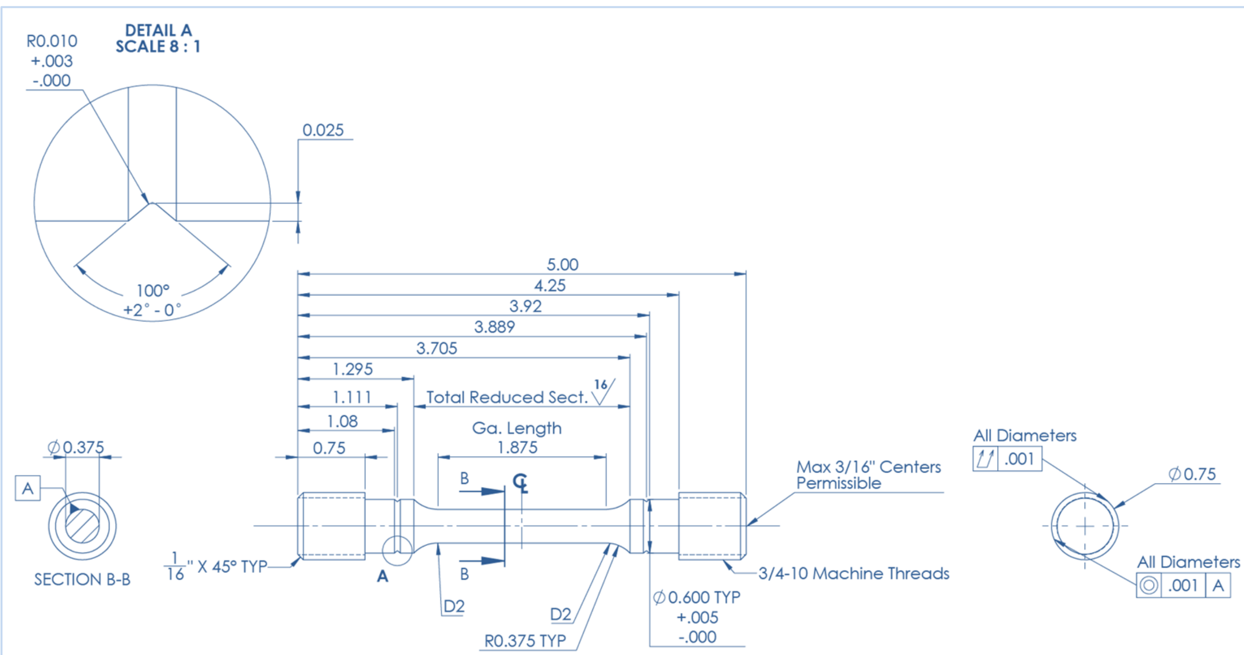


Fig. 1. Creep specimen geometry for Alloy 709 Code Case testing at ORNL. Dimensions are in inches.

In FY 2021, all 24 creep rupture tests on ESR1150-AH tasked to ORNL were started and 6 short-term rupture data were produced. At the time of this report, ongoing creep tests on Alloy 709 base metal at ORNL include 18 on ESR1150-AH, 12 long-term tests on ESR1100, and 4 long-term tests on AOD1100. The ongoing long-term creep Code Case tests on ESR1100 and AOD1100 at ORNL are listed in Table 3, and the testing status of ESR1150-AH at ORNL is summarized in Table 4.

Table 2. Creep Code Case testing matrix on Alloy 709 (heat number 58776).

Target Code Case	Target rupture life (h)	Temperature (°C)	Stress (MPa)	Labs involved	Materials being tested at ORNL in FY 2021
Preliminary	Up to 11,000	600–1000	7–380	ANL/INL/ ORNL	ESR1150-AH
100,000 h	Up to 25,000	575–800	35–330	ANL/INL/ ORNL	ESR1100; AOD1100 ESR1150-AH
300,000 h	Up to 68,000	525–800	40–330	ORNL	ESR1100; AOD1100 ESR1150-AH
500,000 h	Up to 110,000	525–800	35–355	ORNL	ESR1100; AOD 1100 ESR1150-AH

Table 3. FY 2021 ongoing creep Code Case testing on ESR1100 and AOD1100 at ORNL.

TN number	Temperature (°C)	Stress (MPa)	Thermocouple	Material
34162	525	355	K	ESR1100
34163	550	330	K	ESR1100
34182	550	285	K	ESR1100
34183	575	285	K	ESR1100
34130	600	200	K	ESR1100
34113	625	155	K	ESR1100
34111	700	90	K	ESR1100
34161	700	80	K	ESR1100
34112	725	80	K	ESR1100
34184	750	60	K	ESR1100
34241	800	40	K	ESR1100
34265	800	35	K	ESR1100
33629	550	309	K	AOD1100
33632	700	88	K	AOD1100
33635	800	38	K	AOD1100
33636	750	58	K	AOD1100

Table 4. FY 2021 creep Code Case testing status on ESR1150-AH at ORNL

TN number	Target Code Case	Temperature (°C)	Stress (MPa)	Thermocouple	Status
TN39478	500,000 h CC	550	250	K	Running
TN39346	500,000 h CC	575	200	K	Running
TN39344	500,000 h CC	675	82	K	Running
TN39345	300,000 h CC	600	175	K	Running
TN39368	300,000 h CC	625	140	K	Running
TN39369	300,000 h CC	750	45	S	Running
TN39370	100,000 h CC	800	35	S	Running
TN38992	100,000 h CC	700	90	K	Running
TN39517	preliminary CC	850	30	S	Running
TN39518	preliminary CC	875	30	K	Running
TN39519	preliminary CC	900	30	K	*Ruptured*
TN39694	preliminary CC	875	24	S	Running
TN39513	preliminary CC	900	24	S	*Ruptured*
TN39501	preliminary CC	925	24	S	*Ruptured*
TN39693	preliminary CC	900	20	S	Running
TN39511	preliminary CC	925	20	S	*Ruptured*
TN39612	preliminary CC	950	20	S	*Ruptured*
TN39842	preliminary CC	925	15	S	Running
TN39692	preliminary CC	950	15	S	Running
TN39512	preliminary CC	975	15	S	*Ruptured*
TN39843	preliminary CC	975	11	S	Running
TN40008	preliminary CC	1000	10	S	Running
TN40007	preliminary CC	1000	7	S	Running
TN39910	preliminary CC	975	15	S	Running

3.2 CREEP RUPTURE TEST RESULTS ON ALLOY 709

For comparison purposes, the Larson-Miller Parameter (LMP) was used to compare all the available creep rupture results on ESR1100, AOD1100, ESR1150, and ESR1150-AH from ORNL, INL and ANL, along with the Nippon Steel NF709 data. The results are shown in Fig. 2. Creep rupture data on ESR1150-AH produced at ORNL in FY 2021 are highlighted with solid symbols. In this plot, the Larson-Miller equation for calculating the LMP was based on Eq. (1):

$$LMP = (temperature + 273.15) * (C + \log(t_r)), \qquad (1)$$

where temperate is in °C and rupture life, t_r, is in hours, and C is assumed to be a constant value of 15.

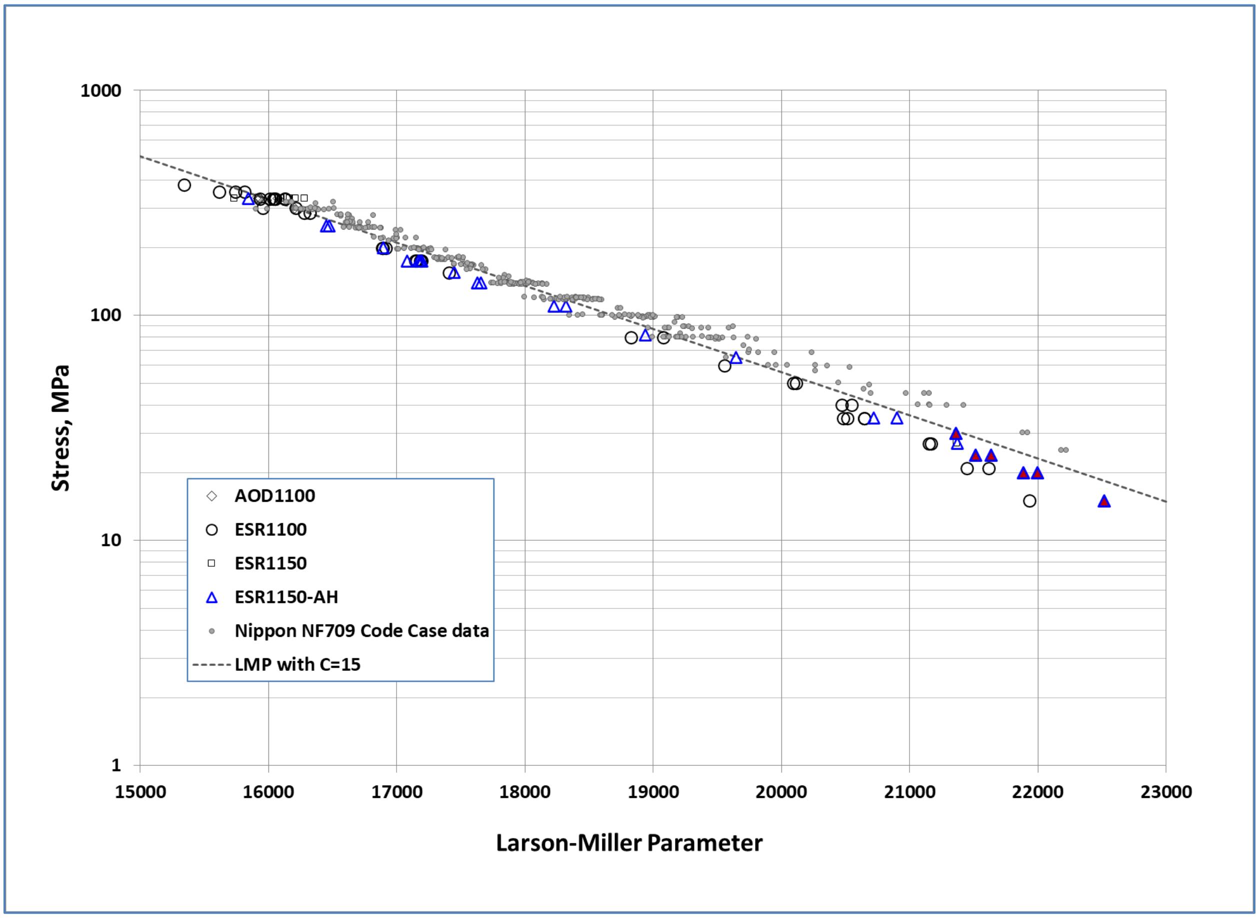


Fig. 2. Comparison of the ESR 1100, AOD1100, ESR1150, and ESR1150-AH creep rupture data with data for Nippon Steel NF709 on the LMP-stress plot.

The results show that this first commercial heat is slightly weaker than Nippon Steel NF709 in terms of creep resistance, since all data points are to the left of those for Nippon Steel NF709, especially at the higher LMP values above 19,000. However, the creep strengths are still significantly higher than the reference material, Type 316 stainless steel. Additional rupture data are needed to fully assess the creep resistance of this first commercial heat of Alloy 709.

4. FATIGUE AND CREEP-FATIGUE CODE CASE TESTING ON ALLOY 709

4.1 FATIGUE AND CREEP-FATIGUE TESTING

To be consistent with testing program conventions, the fatigue and CF testing temperatures were based on US customary units, and testing was conducted at temperatures of 1200°F (649°C), 1300°F(704°C), 1400°F(760°C), and 1500°F(816°C). The fatigue Code Case testing matrix in support of generating temperature-dependent fatigue design curves for Alloy 709 was developed, and the plan is to generate fatigue design curves up to the maximum testing temperature of 1500°F (816°C) (Wang and Sham 2019). In FY 2020, a preliminary fatigue design curve was developed at 1400°F (760°C), based on fatigue results for ESR1100 and ESR1150-AH (Wang et al. 2020); and the results showed that the fatigue design curve of Alloy 709 was comparable to that of Alloy 800H at the same temperature. In FY 2021, fatigue testing at a maximum temperature of 1500°F (816°C) was prioritized and tasked to INL, and fatigue testing at 1300°F (704°C) on ESR1150-AH was initiated at ORNL. In addition, standard CF Code Case testing was started at temperatures of 1200°F, 1300°F, 1400°F, and 1500°F on ESR1150-AH at ORNL and INL to generate data in developing the CF damage interaction diagram.

The specimen geometries for fatigue or CF are shown in Fig. 3. The specimen has a gage diameter of 6.35 mm and a 19.05 mm gage length. All the Code Case testing specimens were machined from the mid-thickness of the Alloy 709 plates along the rolling direction. The fatigue testing followed the ASTM E606-12 standard (ASTM 2012) for conducting strain-controlled fatigue tests, and the CF testing followed the ASTM E2714-13 standard (ASTM 2013) under strain-controlled mode.

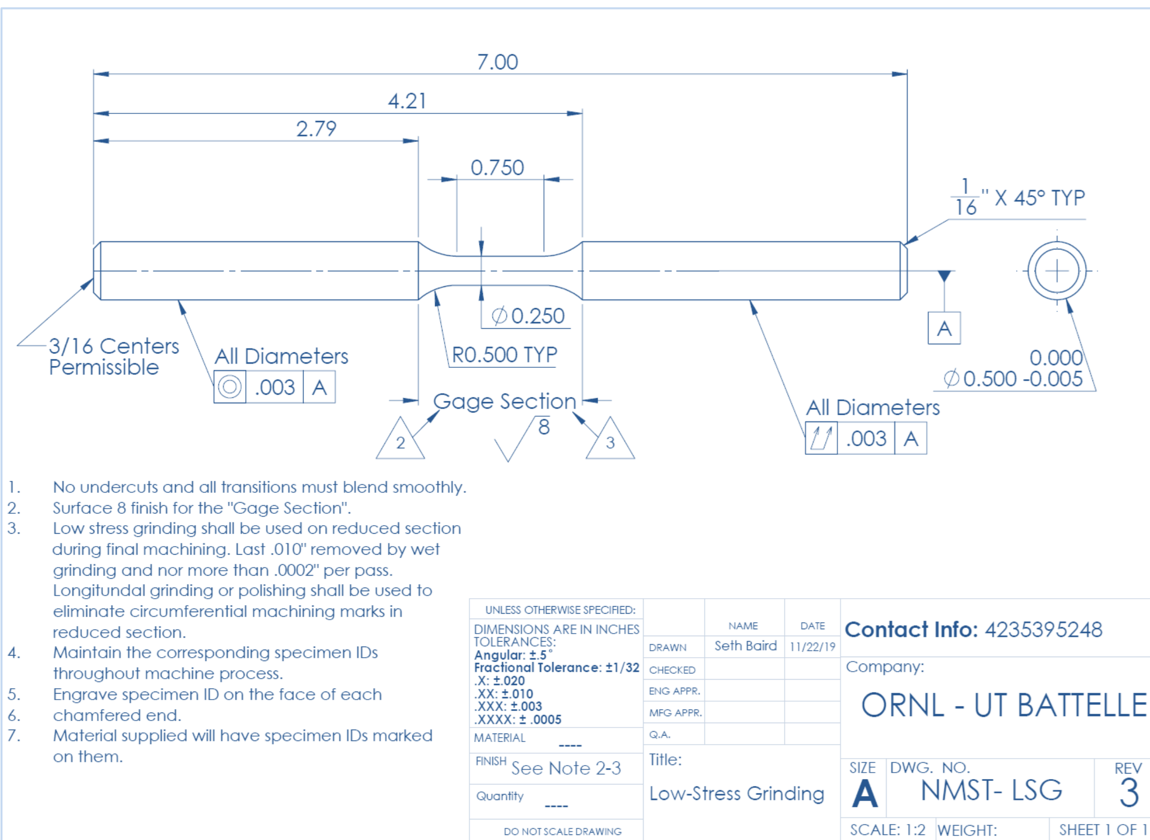
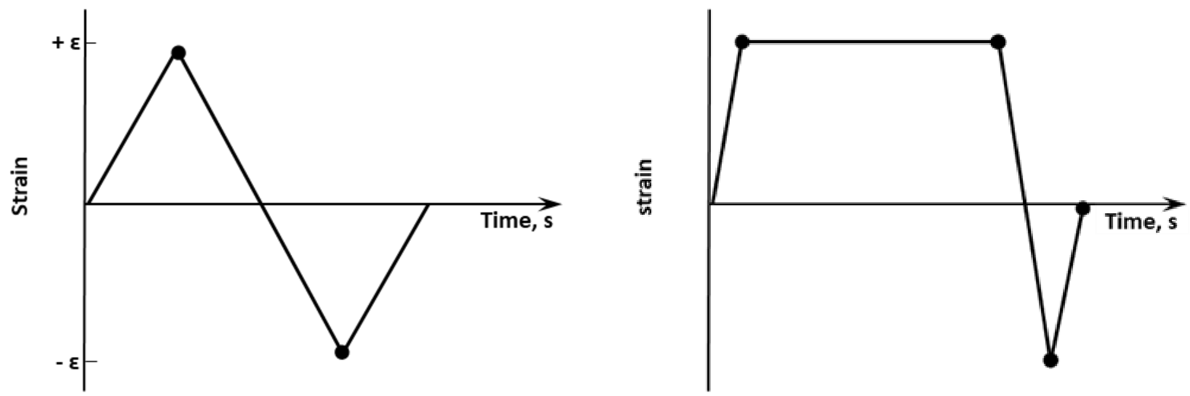


Fig. 3. Standard fatigue and creep-fatigue specimen geometry for Alloy 709 Code Case testing at ORNL. Dimensions are in inches.

The loading profiles for pure fatigue and CF are shown schematically in Fig. 4. The hold-time segment is applied to the maximum tension amplitude for CF testing. The loading profiles are fully reversed profile, i.e., with a nominal loading ratio of R = –1. The nominal strain rate is 1E-3/s unless otherwise noted. The control extensometer has a nominal gage length of 12.7 mm.



(a) (b)

Fig. 4. Strain-controlled fatigue (a) and creep-fatigue (b) loading profile for one cycle.

4.2 FATIGUE TEST RESULTS ON ESR1150-AH AT 1300°F

Fatigue Code Case testing on ESR 1150-AH was initiated at 1300°F (704°C), and failure data were generated at strain ranges of 1.0%, 0.6% and 0.3% at strain rate of 1E-3/s. In addition, because the material was responding elastically at the low strain range of 0.2% at this test temperature, the test was switched to load-controlled mode at an equivalent stress amplitude with a higher frequency of approximately 3 Hz to speed up the testing.

The maximum and minimum stresses as a function of the applied cycles of these fatigue tests are plotted in Fig. 5. Cyclic hardening behavior was observed at the very beginnings of the applied cycles for all the fatigue tests at the strain ranges presented, and the maximum and minimum stress levels remained saturated until the onset of failure initiation.

The fatigue testing parameters and the cycles to failure are summarized in Table 5. The failure criteria based on the 25% maximum load drop were used to determine the cycles to failure. Fatigue testing at a 0.2% strain range had a runout 20,000,000 cycles and the test was interrupted without failure.

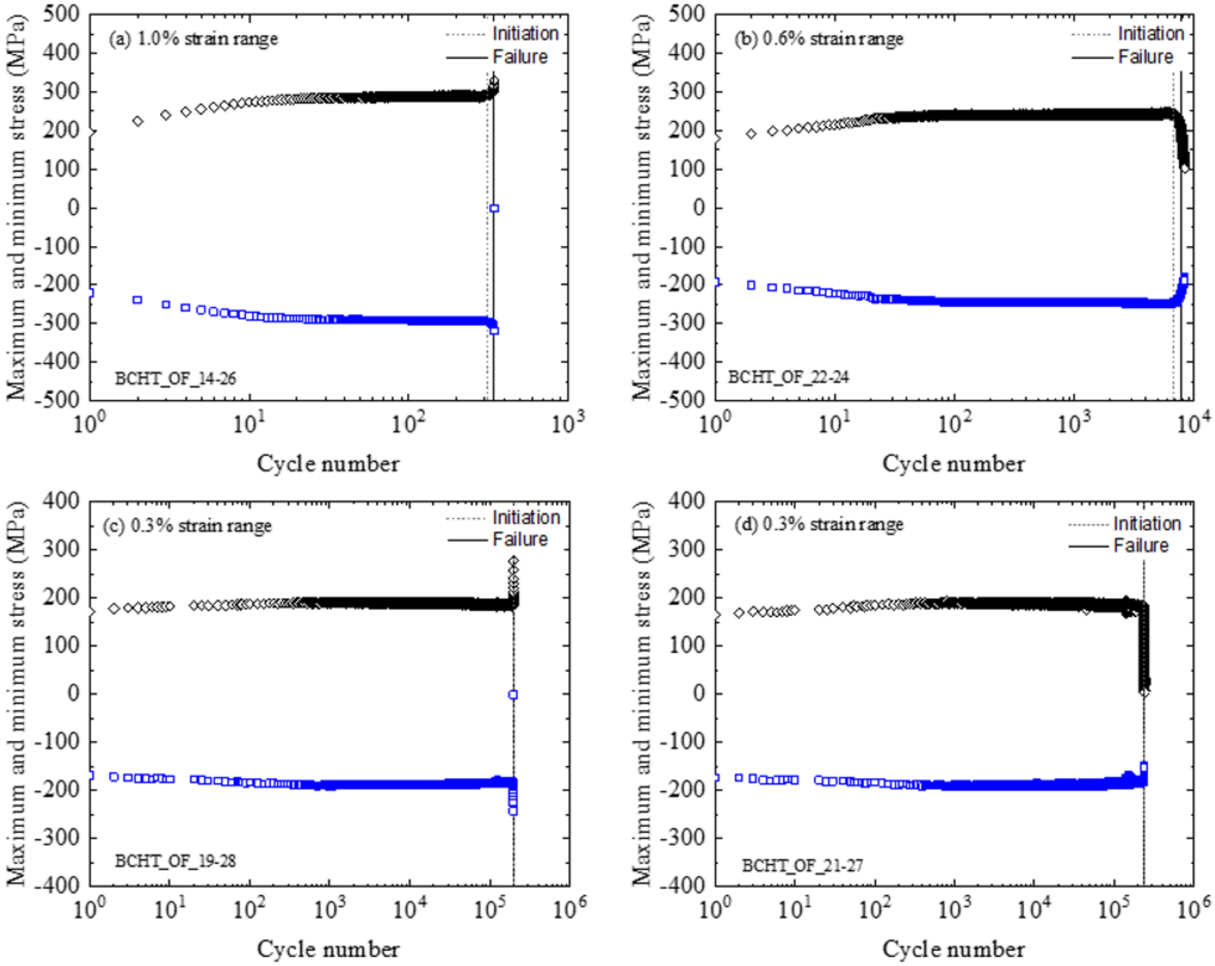


Fig. 5. Maximum and minimum stresses of fatigue tests on Alloy 709 ESR 1150-AH (heat number 58776-3RBC) at strain ranges of 1.0% (a), 0.6% (b), and two tests at 0.3% (c, d) at 1300°F.

Table 5. Fatigue test results of ESR 1150 -AH (heat number 58776-3RBC) at 1300°F.

Specimen ID	Strain range (%)	Cycles to failure*
BCHT_OF_14_26	1.0	343**
BCHT_OF_22_24	0.6	7,948
BCHT_OF_19_28	0.3	197,917**
BCHT_OF_21_27	0.3	238,691
204D_DX-33	0.2	>20,000,000†

*Failure criteria: 25% maximum load drop.

** Failure location was outside the extensometer gage.

†The test was performed under load-controlled mode. The specimen did not fail at 20,000,000 cycles

4.3 CREEP-FATIGUE TEST RESULTS ON ESR1150-AH

4.3.1 Creep-fatigue Results at 1200°F

The hold time effect was evaluated on ESR1150-AH at 1200°F at a nominal strain range of 1.0%. Figure 6 presents the evolution of maximum/minimum stresses, representative hysteresis loops, and normalized stress relaxation curves of representative cycles during the tension-hold segment for specimens tested with tension-hold times of 3600 s, 1800 s, and 600 s, respectively. Note that the third cycle was plotted to represent the beginning of the cyclic loading because of the noise in the first two cycles for strain-controlled tests. The stress relaxation curves were normalized by the stress value at the beginning of the hold time segment of the cycle of interest. The CF testing condition and the results are summarized in Table 6. The CF life decreased slightly from 780 cycles to 575 cycles as the holding time increased from 600 s to 3600 s.

In all cases, cyclic hardening behaviors were observed during the initial 50 applied cycles, as indicated by the increasing maximum and minimum stresses with more applied cycles. After the initial hardening, the material remained cyclic neutral for the remaining applied cycles till failure initiation. As shown in the plots, stress relaxation occurs owing to creep deformation during the tension-hold segment, and the stresses relaxed more rapidly at the mid-life cycle than at the beginning of the fatigue cycles.

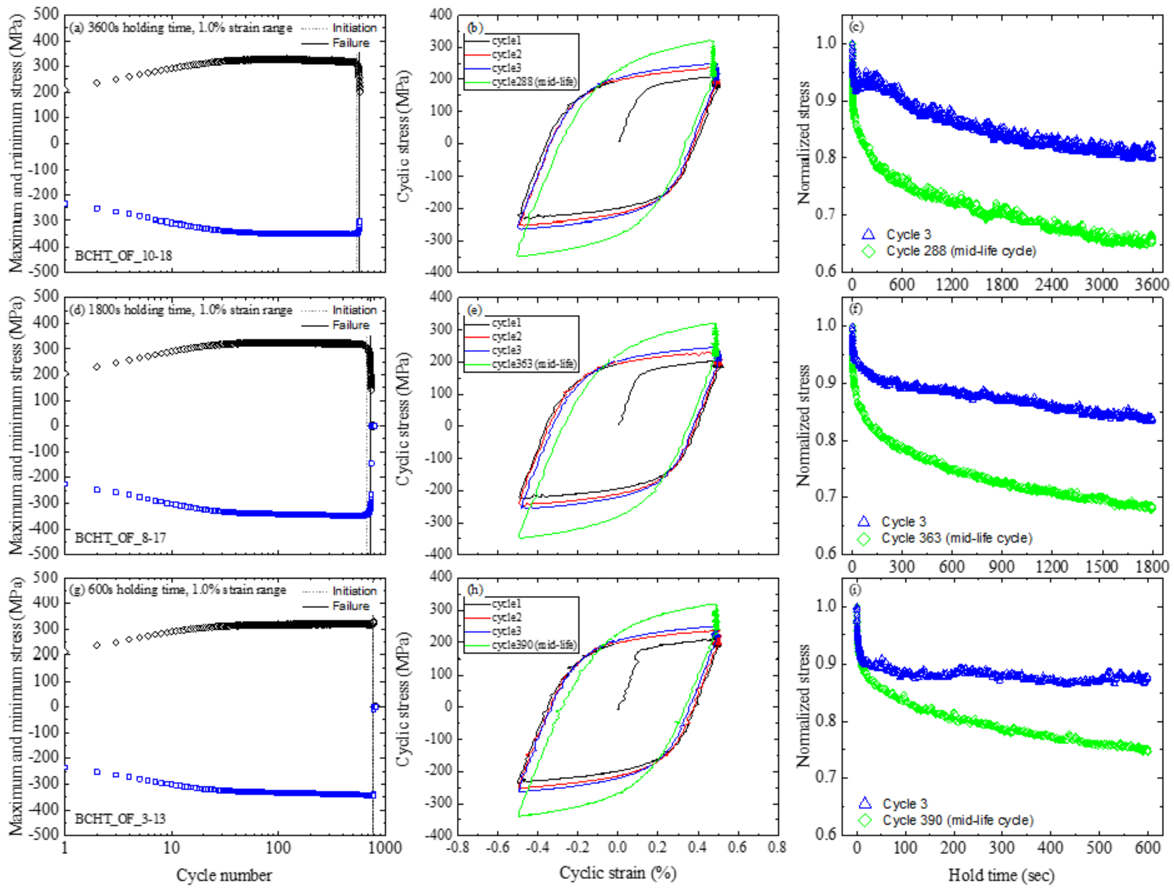


Fig. 6. Maximum and minimum stresses as a function of applied cycles (a, d, g); representative hysteresis loops (b, e, h); and normalized stress relaxation curves (c, f, i) for CF at 1.0% strain range and tension-hold times of 3600 s, 1800 s, and 600 s at 1200°F.

The stresses during the hold segment at the mid-life cycle rapidly decreased with an approximately 20% in the initial 300 s of the hold for all three cases and gradually slowed down for the remaining time of the hold segment. The normalized stress relaxation curves of mid-life cycle are compared in Fig. 7 to assess the influence of hold time on stress relaxation behavior. Interestingly, the mid-life stress relaxation behavior showed insignificant differences between the three tests with different hold times at this strain range of 1% at 1200°F.

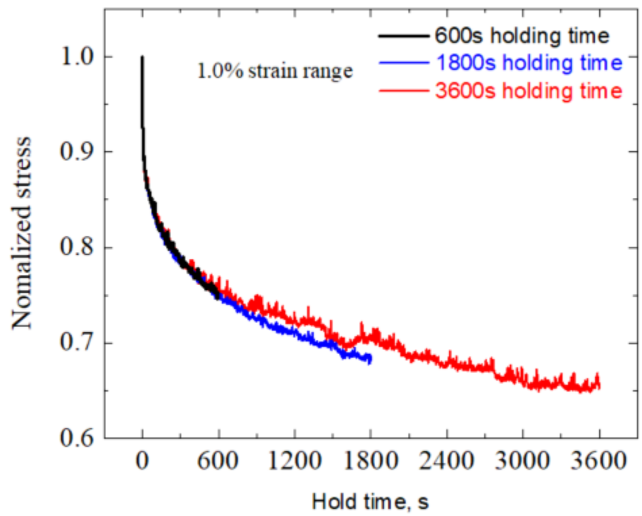


Fig. 7. Comparison of the stress relaxation curves during tension-hold segments at mid-life cycles between 600 s, 1800 s, and 3600 s hold times at a 1.0% strain range at 1200°F.

Table 6. Summary of the CF results for ESR1150-AH at 1200°F.

Specimen ID	Strain range, %	Tension holding time, s	Cycles to failure†
BCHT_OF_10-18	1.00	3,600	575
BCHT_OF_8-17	1.01	1,800	726
BCHT_OF_3-13*	1.01	600	780

* Failed outside the extensometer gage
†Failure criteria: 25% maximum load drop.

4.3.2 Creep-fatigue Results at 1400°F

Three CF tests were completed on ESR1150-AH at 1400°F. The maximum/minimum stresses, representative hysteresis loops, and normalized stress relaxation curves of representative cycles during the tension-hold segment for tests at a nominal strain range of 0.6% and hold times of 1800 s and 600 s are plotted in Fig. 8. The curves for the test at a nominal strain range of 1% and a hold time of 600 s are shown in Fig. 9. The CF testing parameters and the results are summarized in Table 7.

Slight cyclic hardening behavior was observed at the beginnings of the applied cycles at this test temperature of 1400°F. It is evident that the stress relaxation was much faster at this test temperature than at 1200°F for similar loading conditions, and there was significant stress relaxation even at the beginnings of the applied cycles. Additional applied cycles did not significantly enhance the stress relaxation rate, as shown by the comparison of the stress relaxation curves at the mid-life cycle and the third cycle.

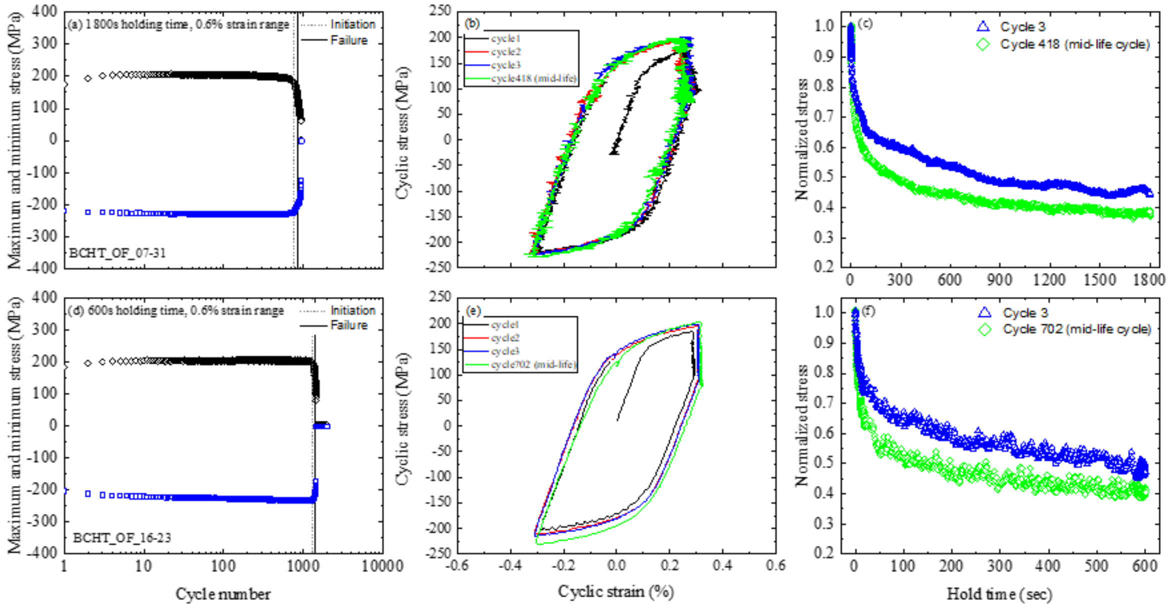


Fig. 8. Maximum and minimum stresses as a function of applied cycles (a, d), representative hysteresis loops (b, e), and normalized stress relaxation curves (c, f) for CF at a 0.6% strain range and tension-hold times of 1800 s and 600 s at 1400°F.

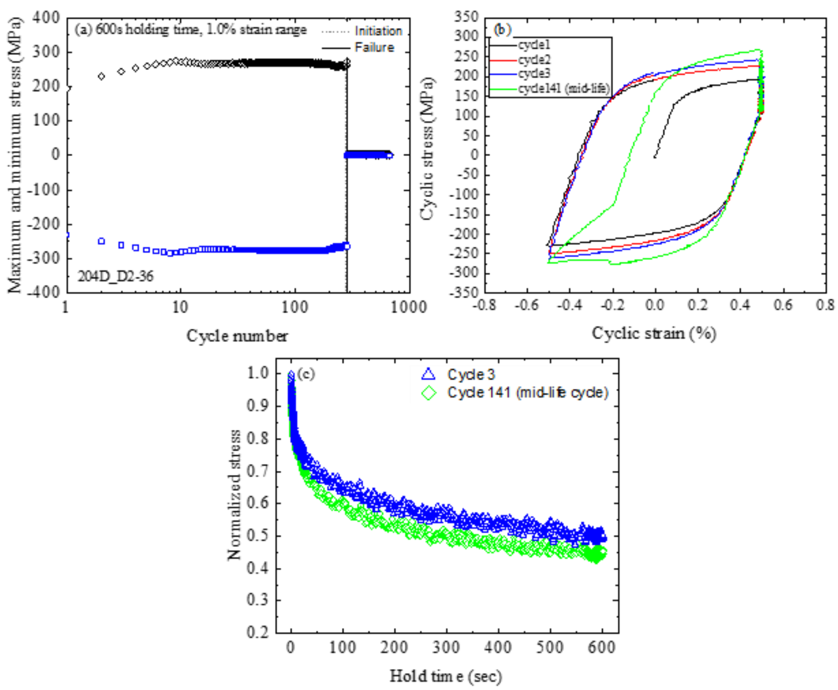


Fig. 9. Maximum and minimum stresses as a function of applied cycles (a), representative hysteresis loops (b), and normalized stress relaxation curves (c) for CF at a 1.0% strain range and a tension-hold time of 600 s at 1400°F.

The CF results were also plotted on the previously developed preliminary fatigue best-fit curve at 1400°F shown in Fig. 7. The influence of the 600 s tension-hold time on the reduction of the failure cycles was similar at these two strain ranges of 1% and 0.6%. Duplicates and additional CF tests at different strain ranges and hold times are ongoing to obtain a complete understanding of the hold time effect, and to provide the required failure data for developing the CF interaction damage diagram.

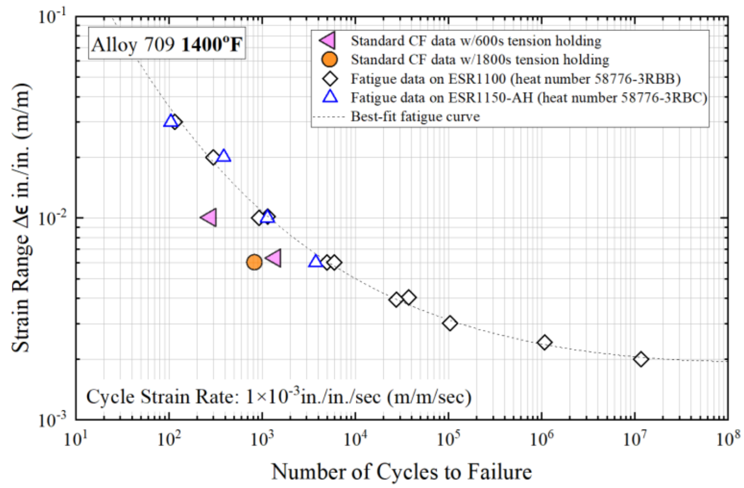


Fig. 10. Fatigue and creep-fatigue data at 1400°F.

Table 7. Summary of the CF results on ESR 1150 -AH at 1400°F.

Specimen ID	Strain range, %	Tension holding time, s	Cycles to failure†
204D_D2-36	1.01	600	282
BCHT_OF_07-31	0.62	1,800	835
BCHT_OF_16-23	0.61	600	1,404

†Failure criteria: 25% maximum load drop.

4.3.3 Creep-fatigue Results at 1500°F

Seven standard CF tests were completed at 1500°F at the nominal strain ranges of 1.0%, 0.6%, and 0.3% with various tension-hold times. The maximum/minimum stresses, representative hysteresis loops, and normalized stress relaxation curves of representative cycles during the tension-hold segment for tests at a nominal strain range of 1.0% are plotted in Fig. 11, and the curves for tests at a nominal strain range of 0.6% are shown in Fig. 12. The normalized mid-life stress relaxation curves for tests at both 1.0% and 0.6% strain ranges are compared in Fig. 13. Plots of the CF test performed at a low strain range of 0.3% and a 600 s tension hold are shown in Fig. 14. A summary of the CF testing parameters and the results is in Table 8.

The results show that at both higher strain ranges of 1.0% and 0.6%, the material showed the highest stress relaxation rates compared with the tests performed under the same loading conditions at lower test temperatures. The stresses relaxed by 50% to 60% during the 600 s hold time at the peak tension amplitude. At 1500°F and higher strain ranges of 1.0% and 0.6%, the material showed the same stress relaxation behavior at the beginning of the test and at the mid-life cycle, with overlapping normalized stress relaxation curves, except for one test at 0.6% with a 600 s hold time. The normalized mid-life stress relaxation curves at both the 1.0% and 0.6% strain ranges in Fig. 13 show that at longer holding times of 1800 s and 3600 s, the stress realxation behavior is almost identical and is slower than that with shorter hold time of 600 s, indicating the same CF damage mechnism at these two longer hold times at these strain ranges in this study.

At a 1.0% strain range at 1500°F, the increase in the tension-hold time from 600 s to 3600 s did not affect the cycles to failure significantly. At a 0.6% strain range, the cycles to failure were reduced when the hold time increased from 600 s to 1800 s; but the hold time effect is not clear when it is further increased to 3600 s, based on the available data.

At a low strain range of 0.3% with a 600 s tension-hold time (Fig. 14), comparing the stress relaxation curves at the beginning of the test and at the mid-life cycle with those at higher strain ranges, the stress relaxation was much slower than at higher strain ranges.

Note that the plan is to duplicate all the tests reported to obtain a clearer understanding of the data scatter and the repeatability of the CF tests under the same conditions. Conventionally, three repeats are performed with the same testing parameters.

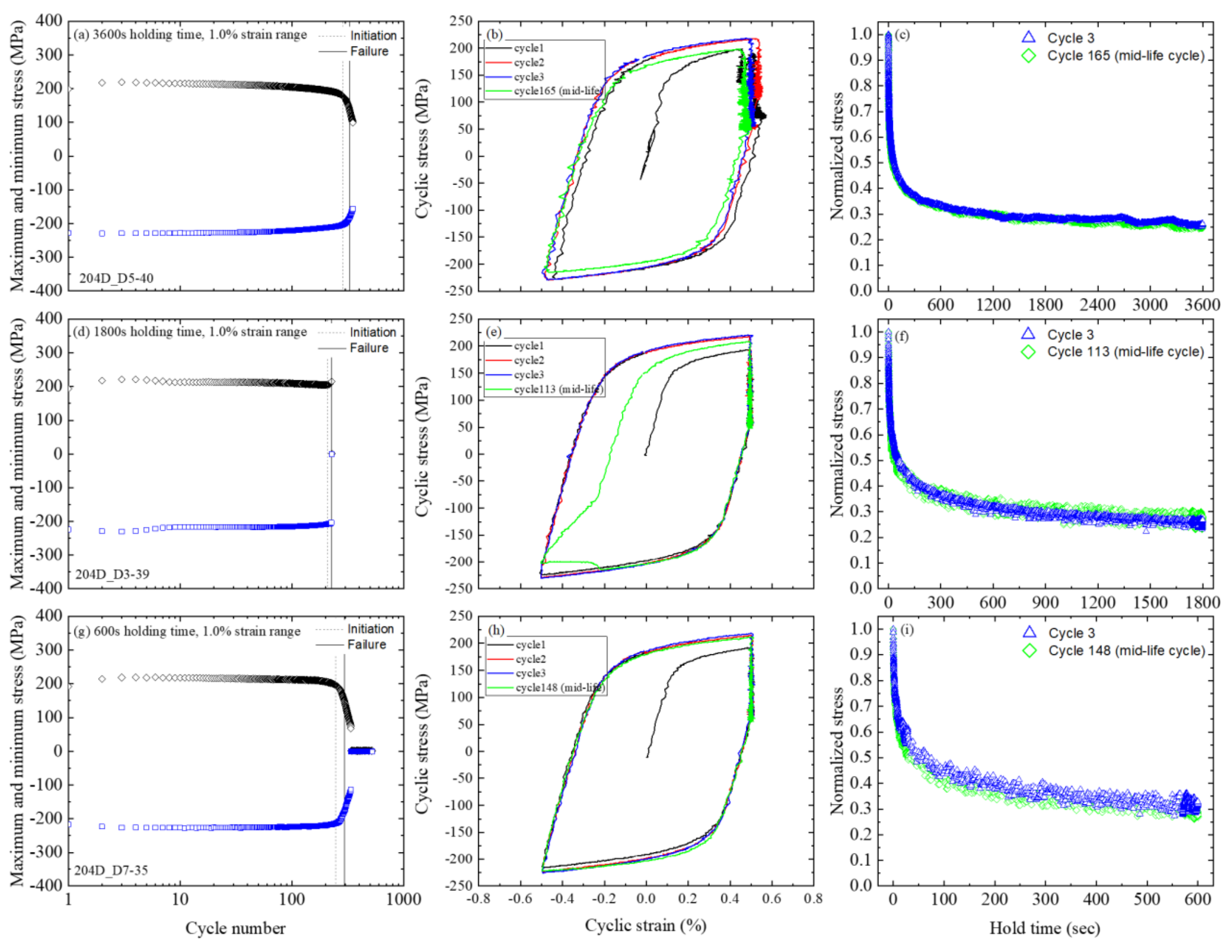


Fig. 11. Maximum and minimum stresses as a function of applied cycles (a, d, g), representative hysteresis loops (b, e, h), and normalized stress relaxation curves (c, f, i) for CF at a 1.0% strain range and tension-hold times of 3600 s, 1800 s, and 600 s at 1500°F.

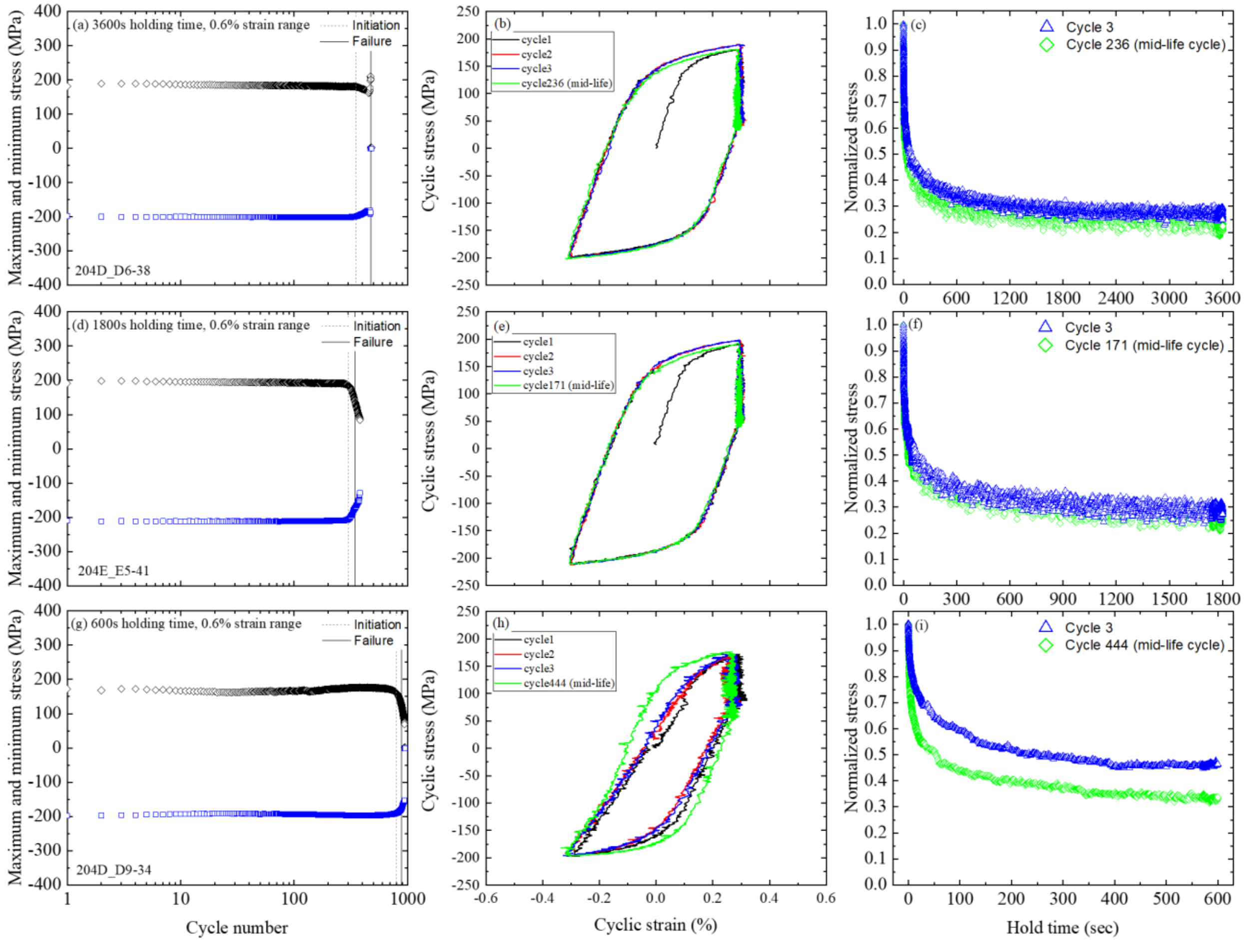


Fig. 12. Maximum and minimum stresses as a function of applied cycles (a, d, g), representative hysteresis loops (b, e, h), and normalized stress relaxation curves (c, f, (i) for CF at a 0.6% strain range and tension-hold times of 3600 s, 1800 s, and 600 s at 1500°F.

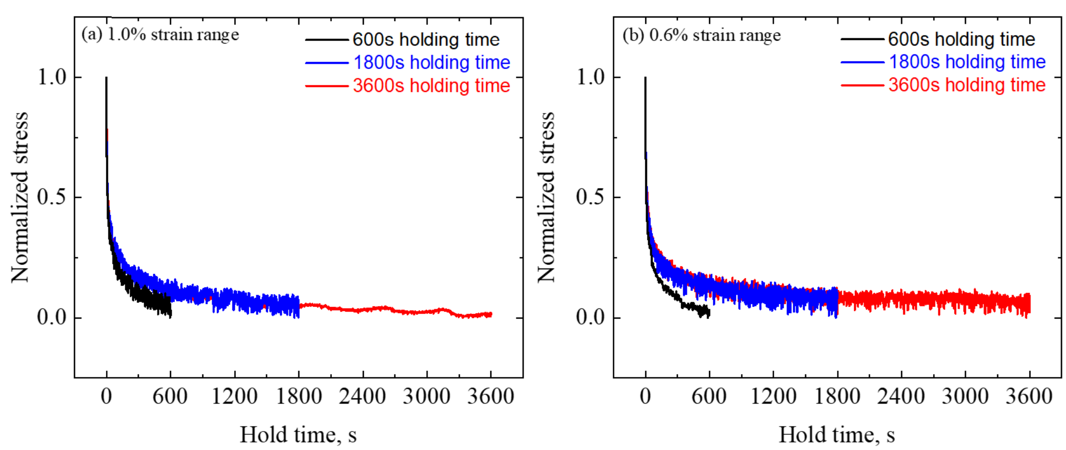


Fig. 13. Comparison of stress relaxation curves during tension-hold at mid-life cycles for CF tests at strain ranges of 1.0% (a) and 0.6% (b) at 1500°F.

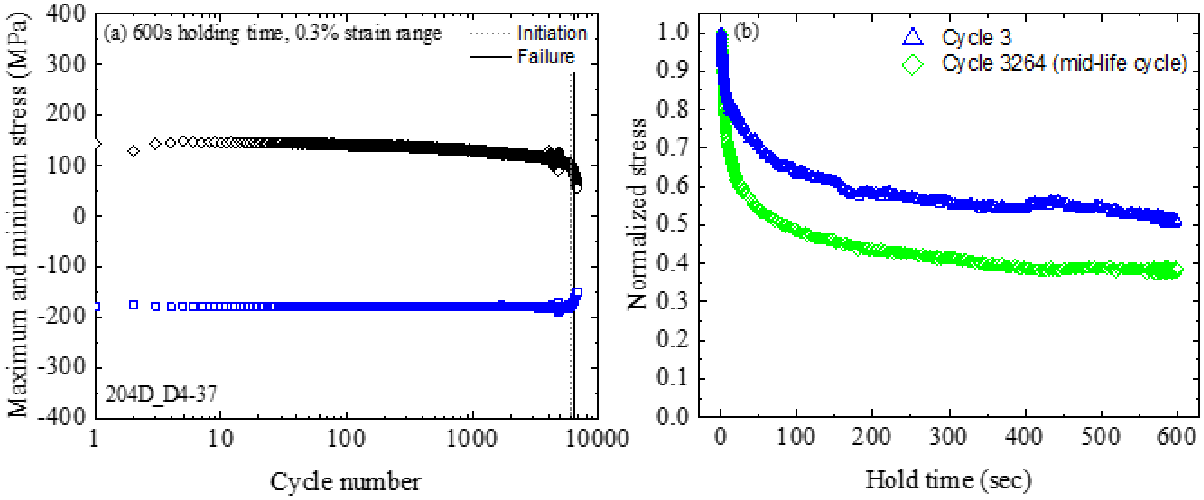


Fig. 14. Maximum and minimum stresses as a function of applied cycles (a) and normalized stress relaxation curves (b) for CF at a 0.3% strain range and a tension-hold time of 600 s at 1500°F.

Table 8. Summary of the CF results on ESR 1150 -AH at 1500°F.

Specimen ID	Strain range, %	Tension holding time, s	Cycles to failure
204D_D5-40	0.99	3,600	330
204D_D3-39	1.02	1,800	226
204D_D7-35	1.01	600	296
204D_D6-38	0.62	3,600	472
204E_E5-41	0.62	1,800	342
204D_D9-34	0.62	600	887
204D_D4-37	0.32	600	6,528

5. SUMMARY

The results from the planned FY 2021 Code Case testing at ORNL in support of the ASME code qualification of Alloy 709 are summarized in this report. A subset of the creep Code Case testing matrix on ESR1150-AH with 24 testing conditions tasked to ORNL were started, and 6 short-term rupture data were produced. At the time of this report, ongoing creep tests of the Alloy 709 base metal at ORNL include 18 tests on ESR1150-AH, 12 long-term tests on ESR1100 and 4 long-term tests on AOD1100. Fatigue and CF Code Case testing continued. Preliminary fatigue test results were produced at 1300°F; CF testing was initiated at 1200°F, 1400°F, and 1500°F, and CF failure data were generated at various strain ranges and hold times.

Creep, fatigue, and CF experiments in support of the ASME code qualification of Alloy 709 will continue in FY 2022 at ORNL.

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