Fabrication and Testing of Two Passively Actuated Creep-Fatigue Surveillance Test Articles

Applied Materials Division

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Prepared by

Mark C. Messner, Argonne National Laboratory

Yoichi Momozaki, Argonne National Laboratory

Ed Boron, Argonne National Laboratory

Guosheng Ye, Argonne National Laboratory

Ting-Leung Sham, Idaho National Laboratory

ABSTRACT

This report describes the fabrication, testing, and analysis of two families of passively-actuated creep-fatigue test articles. These test articles induce cyclic mechanical load in a test section actuated solely through a mismatch in the thermal expansion coefficient of two materials and driven by a change in the specimen temperature. Test articles of this type could provide material degradation data for a materials surveillance program in future operating molten salt reactors, where variations in the reactor temperature caused by normal or upset cycles would provide the temperature change in the sample. The purpose of the current experimental campaign is to demonstrate the feasibility of fabricating realistically-sized test articles, test the articles under repeated thermal cycling to assess their robustness, particularly the reliability of the bimetallic welds, and collect strain data from instrumented samples to validate the methods used to size the test articles to match key features of the mechanical response of operating reactor components. The thermal cycling tests are ongoing but the test data to date suggests the current test article design is viable, robust, and can be successfully designed to match a target mechanical response. Finally, the report describes preliminary work on welding refractory alloys to 316H stainless steel. Replacing the test article driver material, currently Alloy 617, with a refractory would increase the coefficient of thermal expansion mismatch and support further miniaturization of the test articles.

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1 Introduction

The environmental conditions expected in future Molten Salt Reactors (MSRs) pose a challenge to the long-term reliability of the materials used in constructing the reactor structural components [1]. Radiation damage and interactions with the molten salt chemistry may degrade the strength of the component materials over time. One strategy to manage these potentially detrimental mechanisms is to establish a materials surveillance program, aimed at observing and quantifying the change in the strength of the reactor materials by exposing surveillance articles to the reactor environmental conditions [2]. The data from such a surveillance program could then be used to provide reasonable assurance to the plant operators and regulators of the long-term integrity of the key reactor components.

MSRs will experience high temperature cyclic service, with some load following designs experiencing a large number of load cycles over the plant life is anticipated. Past high temperature reactor design campaigns [3] suggest that under these conditions creep-fatigue will be the dominant structural material failure mode. Therefore, a materials surveillance program would provide a means to manage the degradation in the material creep-fatigue strength during reactor operations.

This report describes a key component of such a materials surveillance technology: a family of passively actuated materials surveillance test articles. These test articles induce cyclic loading in a test section, fabricated from the surrogate component structural material, using only the regular change in the reactor coolant temperature, for example during regular startup and shutdown cycles, as the driving force. The test article design applies this cyclic loading using differential thermal expansion – the article consists of two different materials with differing coefficients of thermal expansion, designed to cycle the test material via the difference in expansion with a change in temperature. Test articles of this type could provide the technical basis for a materials surveillance technology deployed to estimate a materials degradation management program.

This report is a companion to a second technical report [4] describing approaches to developing acceptance criteria as well as a procedure for sizing test articles of this type to match the key features of a component mechanical response. The current report specifically describes the design, fabrication, and testing of two different families of test articles and several variants within each family. The two families serve different purposes:

1. The “large” family of test articles have an outer envelope of a 2 in. diameter and a 12 in. length. These articles are too large for use in an actual operating reactor but are sized so that they can be instrumented with strain gages and thermocouples to measure the actual temperatures and induced, mechanical strains during thermal cycling tests and can be easily inspected for damage. The purposes for this family of test articles are:
 - a. Provide validation data for the method used to size the test articles to hit a target strain range delivered to the test section, given a known thermal cycle as input. These sizing methods will be a key technical component of a surveillance technology for implementing materials degradation management programs.
 - b. The larger envelop allows a design that delivers a large strain range to the test material, much larger than what an actual well-designed component would see in service. This increased strain range means we expect the test section to fail in 3,000-

8,000 thermal cycles, providing accelerated test conditions compared to operating components. This failure could then potentially be observed during the current thermal cycle test campaign. A test to failure could verify that the article fulfills the key surveillance requirement of inducing failure in the test section, and not elsewhere in the test article like the tapers or, more critically, the bimetallic welds used to assemble the article.

- c. Provide an article that can be easily visually inspected to ensure the test article in the as-received, post-machining condition was robust without significant damage induced by the machining and joining process and so that we can visually monitor the state of the test article during the thermal cycling test campaign.
2. The “small” family of test articles have an outer envelope of a 1 in. diameter and a 3 in. length. These articles are reasonably sized for use in an operating reactor, but are too small to easily instrument. Future effort will further optimize the test articles by reducing their overall size to provide greater flexibility for placement and support the space constraints in microreactors. The purposes for these test articles are:
 - a. Demonstrate the same fabrication techniques used for the large article can successfully be used to fabricate a smaller article, suitable for use in an operating reactor.
 - b. These test articles are too small to instrument with strain gage and produce a comparatively small strain range. However, we include them in the thermal cycling test campaign to test the article detailing, in particular the taper details, and to test the bimetallic welds. Any failure, even in the test section, over the current test campaign would suggest that the machining and fabrication processes may have introduced substantial defects as we would not expect the test section to fail under the predicted mechanical load for many thousands of thermal cycles. Future work to develop a post-fabrication acceptance procedure and corresponding acceptance criteria for test articles in operating reactors is necessary to support their use in these critical applications.

Chapter 2 describes the design and fabrication of the test articles. Much of this work was accomplished in FY20, so this chapter summarizes information from a previous technical report [5]. However, some additional fabrication work was completed in FY21 and the design predictions of the test article strain range were updated to match the new sizing method developed in the companion report [4].

Chapter 3 then describes the ongoing thermal cycling test campaign on both types of test articles. The chapter describes and interprets the data collected to date. The thermal cycling testing is ongoing and will continue into FY22, aiming to produce failure in at least one of the large test articles.

Chapter 4 summarizes modeling work aimed at validating the test article sizing procedures, interpreting the experimental data, and assessing the potential impact of the various test article detailing options described in Chapter 2.

Finally, Chapter 5 summarizes the results described in this report and discusses potential future work. This chapter contains a section summarizing preliminary work on bimetallic welding of

refractory materials to an ASME Class A structural material. The objective of this preliminary work is to provide more geometric flexibility in the test article design by maximizing the difference in thermal expansion between the two test article materials.

2 Test Article Design and Fabrication

2.1 Test article design

Figure 2.1. Basic test article design showing a cross-section of the three key sections (test, driver, and casing).

Figure 2.1 shows the basic concept of the test article in a cross-section view. The article has three regions:

1. The test section, fabricated from the same materials as the structural component in the reactor. This report refers to this material as the “surrogate material.” For the present campaign this material is 316H stainless steel.
2. The driver, fabricated from a material with a lower coefficient of thermal expansion than the test material. The current test article driver is the Ni-based Alloy 617.
3. The casing, fabricated from the same material as the test section.

For this design, heating the test article delivers alternating tension and compressive load to the test section via differential thermal expansion. This is a critical requirement of the design to mimic the stresses experienced in actual reactor components during operation.

Our previous report [5] describes the geometric design of the two families of test articles. The basic process was:

1. Size the gross test article geometry using a simple 1D sizing model. Both test articles were sized to maximize the strain range delivered to the test section by the planned thermal cycle while respecting fabrication constraints.

- Convert this gross geometric design to a detailed test article geometry. This includes converting the 1D bar lengths and cross-sectional areas to a smooth, tapered transition and introducing details for mounting strain gages and thermocouples.

This report labels the test articles with a combination of the test article family (small or large), a short description of the detailing options, and a test article number. Figure 2.2 shows the different test articles and matches each article to the label used to refer to it in this report.

Figure 2.2. Various test article configurations, here shown without casings. The large samples without slots are not shown, but are similar.

Figure 2.3 and Figure 2.4 show the strain range predicted for large and small test articles based on the original simplified sizing model and the original assumption for the thermal cycle in the form of a stress-strain hysteresis loop. This original sizing model used a 4-bar description of the geometry (see Figure 2.5b). The FY21 companion report describes an updated 3-bar sizing model [4]. We also now have the actual thermal cycle data available to update the strain range predictions.

Figure 2.3. Previous prediction for the steady response of the large test article family [5]. Predicted total strain range: $\Delta\varepsilon = 0.007$.

Figure 2.4. Previous prediction for the steady response of the small test article family [5]. Predicted strain range: $\Delta\varepsilon = 0.00055$, though these articles are not instrumented and so this strain range cannot be experimentally validated.

Figure 2.5 illustrates the challenge in converting from a simplified 1D “bar” description of the test article used in the sizing model to the actual tapered bar geometry. We discuss this challenge in the previous report [5] for the previous 4-bar model. For the new 3-bar model the challenge is converting the length and area of the test and driver bars to a smooth taper or, equivalently, converting the smooth taper to stepped bar lengths and cross-sectional areas.

Figure 2.5. Illustration of how the full test article geometry (a) maps to the 4-bar model used previously to size the test articles (b) and to the new 3-bar model (c) described in [5]. The 4-bar model uses an extra bar to better-represent the taper in the test section (red). However, the 3-bar model is easier to derive analytical sizing formula.

Chapter 4 discusses the map between the stepped bar and tapered geometries in detail. For now, we use a simple rule based on our previous work on the 4-bar model. This simple map attributes one-third of the length of the taper to the test bar and similarly increases the cross-sectional area of the inner bar by averaging the inner bar diameter with average diameter of this one-third of the taper.

Figure 2.6 then plots the updated prediction of the strain range in the large article using the new 3-bar model, this geometric map, and the actual test article temperature history recorded for article T1. If the experimental strain range matches this prediction, perhaps using an improved geometry mapping rule, then this would validate the test article sizing model proposed in [4].

Figure 2.6. Updated prediction for the strain range in the large family of test articles using the new 3-bar sizing model and the actual test article thermal history. Predicted total strain range: $\Delta\epsilon = 0.008$.

2.2 Test article fabrication

In this section, the details of the test article fabrication (the second family or “large” and third family or “small” test articles as defined in [5]) are discussed. Design considerations and actual design details were previously reported in [5] and will not be repeated here.

2.2.1 The second family of test articles

As described in Section 3.2.3 of [5], the machining technique to produce a smooth, but with multi radii surface was established using practice pieces at Argonne Central Shop (ANL-CS). The previously friction welded bars for the second family of test articles (large samples) were machined to the dimensions and inspected to check their dimensional accuracy at ANL-CS. Each sample is named as shown in Table 2.1.

Table 2.1. Large sample names (ID) and their descriptions.

Sample ID	Description
S1	Large sample with step transition without slots #1
T1	Large sample with taper transition without slots #1
T2	Large sample with taper transition without slots #2
SS1	Large sample with step transition with slots #1
SS2	Large sample with step transition with slots #2
TS1	Large sample with taper transition with slots #1
TS2	Large sample with taper transition with slots #2

The samples, S1 and T1 were the first two samples that were machined to the dimensions and their dimensional accuracy was extensively measured to check the adequacy of the machining process (see Figure 2.7). The inspection confirmed that the machining process has demonstrated sufficient accuracy and was adequate for the purpose of the project, see Figure 2.8 and Figure 2.9.

Figure 2.7. Measurement locations to check the dimensional accuracy of the samples (step transition sample shown, taper transition samples are without locations C and G).

Figure 2.8. Measurements of the sample S1 indicates the dimensional errors are within 2%, sufficient for the project. Note that relative errors were checked at 4 different circumferential positions at each measurement point.

Figure 2.9. Measurements of the sample T1 indicates the dimensional errors are within 0.5%, sufficient for the project. Note that relative errors were checked at 4 different circumferential positions at each measurement point.

Once the accuracy of the machining process was confirmed sufficient, the rest of the samples were machined to the dimensions. Then another set of inspections but only around the gage sections was performed for all the samples (locations D, E, F, and X if applicable), see Figure 2.10. The results indicate that all the samples were precisely machined and the slots were cut with a small positive margin as specified such that the presence of the slots does not weaken the gage section, see Figure 2.11.

Figure 2.10. Details of the measurement locations along the gage section (Taper transition sample shown, step transition samples similar).

Figure 2.11. Sample dimensional variances at D, E, F, and X. Note S1 and T1 were measured differently from the rest of the samples. This may be the reason why their deviation appear larger.

Each casing was subsequently machined at ANL-CS to fit over the corresponding sample rod, see Figure 2.12. All the parts were then brought to a local electron-beam welding shop (Sciaky, Inc.) to e-beam-weld each rod to the corresponding casing, see Figure 2.13 and Figure 2.14.

Figure 2.12. All large samples before shipping to the e-beam weld shop. 2 rods were inserted in their corresponding casing (left 2 casings in the photo).

Figure 2.13. A large sample being e-beam welded in a vacuum chamber at the local shop. The sample is seen at the bottom of the image.

Figure 2.14. E-beam-welded large samples, ready to install a strain gage and a thermocouple. Each bottom shows the circular weld, joining the gage-transition rod and the casing.

As described in the previous report, new high temperature strain gages were purchased. They are user spot-weldable design and the strain gage was installed on each sample at ANL, see Figure 2.15. Note that because of the lack of the slots, the KHCR strain gage could not be installed on

the sample S1 due to the bending limitation of the gage (see Section 3.2.1.2 of [5]). S1 (step transition without slots) is a control sample against SS1 and SS2 (step transition with slots) to assess the effects of the presence of the slots to the performance of the sample, if any.

Figure 2.15. Fully instrumented sample. Strain gage and thermocouple sheaths are seen on the casing. The strain gage was spot welded on the gage section of the test section.

2.2.2 The third family of test articles

As described in Section 3.3.3 of [5], the friction welded bars for the third family of test articles (small samples) were prepared by the outside friction welding company (American Friction Welding or AFW). Once the adequacy of the machining process was demonstrated (see the previous section, 2.2.1), the bars were machined to the dimensions at ANL-CS but unlike the large samples, only quick inspections but no detailed inspections were performed afterward. The purposes of the third family test articles are:

1. To demonstrate the manufacturing capability to fabricate a small test article, which could be used in an operating reactor
2. To demonstrate that the well-designed test article actually fails in the gage, and not elsewhere in the sample

and not to accurately measure the history of the strain, as we cannot affix a standard strain gage over the test section.

Each sample is named as shown in Table 2.2.

Table 2.2. Small sample names (IDs) and their descriptions.

Sample ID	Description
SSS1	Small sample with step transition #1
SSS2	Small sample with step transition #2
SST1	Small sample with taper transition #1
SST2	Small sample with taper transition #2

Each casing was also machined at ANL-CS to fit over the corresponding sample rod, see Figure 2.16. All the parts were then brought to Sciaky to e-beam-weld each rod to the corresponding casing. During assembly prior to the e-beam welding, unfortunately one sample (SST1) was damaged and we have only 3 small samples for the thermal cycling test (Figure 2.17).

Figure 2.16. All small samples before shipping to the e-beam weld shop.

Figure 2.17. E-beam-welded small samples. One sample (SST1) was damaged.

3 Thermal Cycle Testing

This chapter discusses the details of the thermal cycling tests on the small and large families of test articles. Most of the hardware remain the same as previously described in ANL-ART-198 [5] and the explanation of the hardware will not be repeated here. The major differences are the new high temperature strain gages and hardware modifications in the data acquisition system to properly accept the analog signals from the new strain gages. The experimental procedure was also modified to perform the thermal cycle testing more efficiently (more cycles within a given time without compromising the purpose of the experiment).

3.1 Changes in the experiment setup

The setup consists of:

1. The furnace to provide programmed heat cycle to the articles,
2. The data acquisition system to collect the strain gage readings and the temperature readings,
3. The instrumentation, which include the strain gages and the thermocouples attached to the articles,
4. The reference rods, and
5. The samples.

Since the previously used strain gages failed prematurely, a different brand high temperature strain gage (KHCR series from Kyowa Electronic Instruments) is used in this test. Because of the mismatch in the excitation voltage that KHCR strain gages require and the excitation voltage that our Yokogawa-Dataforth system produces, a new custom voltage source was constructed and inserted between the Dataforth modules and the strain gages. These differences are discussed in the next sections.

3.1.1 *Change in the data acquisition system*

The same Yokogawa GM10 is used as a data acquisition system. The modules combined with the GM10 are Dataforth SCM5B38 strain gage input modules for a full bridge strain gage with the excitation voltage of 3.333 V. KHCR strain gages are to be used with either 2 or 5 V excitation voltage whereas the standard Dataforth modules produce either 3.333 or 10 V. As the excitation voltage becomes higher, the heat generation within the gage increases. This can be a critical factor to the longevity as well as the accuracy of the gages since the gages will be operated at a high temperature range for an extended period of time, thus it was judged to run the gages at 2 V. The heart of the voltage source is a Texas Instruments REF2041 voltage reference (Figure 3.1) and can output a stable 2.048 V.

3.1.2 *Change in the instrumentation*

The new high temperature strain gage KHCR series is from Kyowa Electronic Instruments Co., Ltd. Kyowa gages are supposed to be paired with Kyowa's strain gage instrument to properly collect the data. An instrument, Kyowa UCAM-60 was purchased for data collection, but we observed several unexpected problems with the UCAM and were corresponding not certain of its long-term reliability. Since the existing Yokogawa GM 10 and Dataforth based system has been reliably operating, we have decided to use the Yokogawa-Dataforth system with KHCR strain gages. To properly read Kyowa gages with the Yokogawa-Dataforth system, we had to do two things:

1. Matching the excitation voltage. Kyowa gages use either 2 or 5 V excitation voltage (see Section 3.1.1), whereas the standard Dataforth modules produce either 3.333 or 10 V,
2. Calibrating the Yokogawa & Dataforth system against UCAM to confirm that the data read by the Yokogawa-Dataforth system accurately match the data read by the UCAM.

Item 1 was described in Section 3.1.1. Item 2 was tested by providing a constant strain to the Kyowa gage and having the UCAM register its value. Then when the Kyowa gage is connected to the Yokogawa-Dataforth system and the same strain is given to the gage, the Yokogawa-Dataforth system must be adjusted so that it registers a strain value very close (or ideally identical) to the value that the UCAM registers. However, applying a real strain to a strain gage is not a trivial task.

Instead, the shunt-calibration is a common method to produce an electronically equivalent resistance change in the strain gage to simulate an application of a certain strain to the gage. In general, assuming the nominal gage resistance and gage factor (for example, 120 Ω and 2, respectively) of the gage, see Figure 3.4(A), a shunt resistor value can be calculated for a specific strain value, for example, see [6]. Connecting the shunt resistor in parallel with the gage element produces the same electronic signal (analog voltage) in the gage as if the specific strain was applied to the gage.

During the calibration process (Item 2 above):

1. Prepare a shunt resistor corresponding to a strain value near the maximum value of the Yokogawa-Dataforth system (for example, a few thousands $\mu\epsilon$). This shunt resistor is to set the span of the instrument,
2. Prepare a few more resistors that correspond to smaller strain values to check the linearity of the Yokogawa-Dataforth system,
3. With the UCAM, the simulated strain value of the gage with the span-setting shunt resistor is read to confirm that the actual strain value observed is very close to the corresponding strain value,
4. Connect the gage with the span-setting shunt resistor to the Yokogawa-Dataforth system and set the span as the strain obtained in Step 3,
5. With the other resistors prepared in Step 2, check if the values registered by the UCAM are very close to the values read by the Yokogawa-Dataforth system to verify linearity.

In reality, the KHCR gage contains a bridge adaptor circuit with various compensation resistors and is different from the ideal, full Wheatstone bridge circuit, see Figure 3.4. Thus, the standard method to calculate the relationship between the shunt resistor value and corresponding simulated strain, which assumes the Wheatstone bridge circuit with 4 equal resistors, introduces errors.

Figure 3.4. (A) Typical strain gage equivalent circuit and (B) actual equivalent circuit for a KHCR strain gage with the bridge adaptor.

Fortunately, each Kyowa KHCR gage comes with its own datasheet and the detailed information about its bridge adaptor circuit (see Figure 3.5). Therefore, by taking additional resistance measurements of each gage and performing a specific circuit analysis, the shunt resistor value can be precisely calculated and more precise calibration can be performed.

KHCR		Half Bridge High Temperature Strain Gage TEST DATA SHEET	
Model: KHCR-5-120-G16-16 C2MV Inspected date: September 10, 2020 Temp.: 23degC Humid.: 34%RH Adaptable thermal expansion coefficient: 16.2 ppm/degC Temperature compensation range: 25- 750degC		Serial No.: D629 Inspector: <i>T. Hoshina</i> Supervisor: <i>J. Anai</i>	
MI cable length: 2.1m Gage factor at room temp. (including cable resistance): 1.59 Gage resistance R_{AL} : 128.1 ohm Compensating resistance R_{TC} : 1.58 ohm(+) Input/Output resistance of bridge adaptor Input: 120.0ohm		Soft cable length: 0.5m Standard deviation : 0.04 R_{DL} : 127.1 ohm R_{LC} : 26100 ohm(-) R_{BAL} : 3.09 ohm(+) Output: 130.2 ohm	

Estimated curve of thermally-induced Apparent Strain(e_{app}) & Gage Factor(G.F.)

Length of a MI cable heated portion		temperature (degC)									
		25	100	200	300	400	500	600	700	750	
e_{app} ($\mu m/m$)	0.5m	0	-117	-208	-151	-56	-8	8	58	93	
e_{app} ($\mu m/m$)	1.0m	0	-149	-269	-232	-147	-99	-76	-19	18	
e_{app} ($\mu m/m$)	1.5m	0	-178	-320	-288	-195	-126	-75	4	48	
G.F.	0.5m	1.59	1.57	1.51	1.46	1.41	1.37	1.32	1.27	1.24	
G.F.	1.0m	1.59	1.55	1.48	1.40	1.34	1.29	1.23	1.17	1.14	
G.F.	1.5m	1.59	1.54	1.44	1.35	1.28	1.21	1.15	1.09	1.06

Approximate equation of thermally-induced apparent strain & gage factor

$$e_{app} : 2E+06 \times (0.49356 - J)$$

$$G.F. : A \times D / (D + F + 1.58)$$

$$A : 1.764 \times (9.96020E-01 + 2.36441E-04 \times T - 3.33334E-06 \times T^2 + 1.01025E-08 \times T^3 - 1.31419E-11 \times T^4 + 6.07851E-15 \times T^5)$$

$$B : 4.03354E+01 - 2.47802E+00 \times T + 3.98447E-03 \times T^2 - 1.46758E-06 \times T^3$$

$$C : 106.173 + 1.81028E-02 \times T - 1.41851E-06 \times T^2 - 8.53360E-09 \times T^3$$

$$D : 1.00789E+00 \times C \times (1 + (A \times (K - M) \times (T - 25) + 2 \times B) \times 1E-06)$$

$$F : 1.02325E+01 + L \times (3.07932E-02 \times (T - 25) + 2.71446E-05 \times (T - 25)^2 - 3.46995E-08 \times (T - 25)^3 - 3.02527E-23 \times (T - 25)^4)$$

$$G : (D + F + 1.58)$$

$$H : (C + F) \times (F + 26100) / (C + 2 \times F + 26100)$$

$$J : H / (G + H) \times (1 - F / (26100 + F))$$

$$K : 16.2 + 1 / 300 \times T$$

$$M : 12.60465 + 4.14541E-02 \times T - 2.37775E-04 \times T^2 + 5.96835E-07 \times T^3 - 6.56387E-10 \times T^4 + 2.66095E-13 \times T^5$$

※T: Centigrade temperature, T²: square of T, L: Length of a MI cable heated portion

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Figure 3.5. One of the datasheets for a KHCR strain gage. Detailed information about the strain gage are available.

We found that the circuit analysis based on the real equivalent circuit can help calibrate the Yokogawa-Dataforth system so that the Yokogawa-Dataforth system can correctly read the KHCR gages and its readings match with the UCAM readings within 0.2% in the range between $\sim -7000 \mu\epsilon$ and $\sim 7000 \mu\epsilon$, see Figure 3.6.

Figure 3.6. Comparing the reading from the Yokogawa-Dataforth system and the reading from the UCAM. The errors are within 0.2%.

3.2 Experimental procedure

Before starting the first run, several preliminary furnace runs were conducted to identify the best thermal cycle pattern. The two reference samples were placed in the furnace and the sensors were connected to the data acquisition system. Since a simulation indicated that the number of thermal cycles required to break the samples is expected to be a few thousands cycles and the effects of having the soak time (1 hour in the previous test) are not significant, it was decided to eliminate the soak time to reduce the run time. Accordingly, the furnace was programmed to keep repeating a thermal cycle without a soak time, which is:

1. Heat up to 700 °C at 1 °C per min.,
2. Turn the power off immediately after reaching at 700 °C to cool down to 500 °C, and
3. Start heating again at 500 °C.

The preliminary runs showed that there is some temperature difference between the furnace temperature (which controls the furnace) and the reference sample temperatures. The actual temperature cycle the samples experienced was between $\sim 665^{\circ}\text{C}$ and $\sim 520^{\circ}\text{C}$. This is expected because of the thermal mass of the reference samples and the lack of soaking time. To further investigate the effects of the thermal mass of the samples, one large sample with only one thermocouple (S1) was also placed in the furnace and additional preliminary runs were conducted (see Figure 3.7).

Figure 3.7. Reference samples and large sample with the heat shields in the furnace, ready for the preliminary furnace runs.

It turned out that the temperature difference among the samples are not as significant as the temperature differences between the samples and the furnace. The furnace program was modified and confirmed adequate (Figure 3.8):

1. To heat up to 735°C at 1°C per min.,
2. To turn the power off immediately after reaching at 735°C to cool down to 480°C , and
3. To start heating again at 480°C .

Figure 3.8. Reference and large sample temperatures during one 480 °C -735 °C thermal cycle. The data shows only small temperature variations among the samples despite the difference in the sample masses.

Once it was confirmed that the overall system was functioning as expected, all the rest of the second family test articles (total of seven) and one of the third family test articles (SSS1) were placed in the furnace for the first run, see Figure 3.9 and Figure 3.10.

Figure 3.9. All the samples installed in the furnace (without the heat shields for clarity). One small sample is seen on the right. Note one of the large samples (on the left) underwent preliminary furnace cycling to establish the proper heating and cooling pattern and shows the signs of the prior thermal cycling.

Figure 3.10. All the samples with the heat shields, ready for the first run.

During the first run:

1. The temperature was raised from the room temperature to 500 °C at the rate of 1 °C per min,
2. The temperature was held at 500 °C for at least a few hours to stabilize all the temperatures,
3. The temperature was raised to 735 °C at the rate of 1 °C per min,
4. Immediately after the furnace reaches 735 °C, the furnace was allowed to cool to 480 °C,
5. When the furnace temperature drops to 480 °C, the process goes back to Step 3 above, producing the sample temperature cycle between 650 °C and 500 °C.

3.3 Data collection and results

The first run started on 05/24/2021. During the run, strain gage readings and temperature readings were collected. These data collected over the first few cycles are plotted in Figure 3.11 and Figure 3.12. Figure 3.11 and Figure 3.12 show the temperature history and the corresponding raw strain data over the time, respectively. Figure 3.11 shows that the correct sample temperature cycling between ~500 °C and 650+ °C was achieved. Figure 3.12 shows that the measured strain also cycles with the temperature cycle, confirming that everything is working as designed. Note that the value of the strain change over a thermal cycle is $> \sim 1000 \mu\epsilon$ and is larger than the strain change observed in the previous report (on the order of 100 $\mu\epsilon$, see [5]), indicating the effectiveness of the design improvements.

Figure 3.11. Temperature history of the run during the first few cycles. The furnace temperature is shown by the dark blue dots and all other data are for the sample temperatures. The sample temperatures show only a small temperature spread.

Figure 3.12. Raw strain data collected during the first few cycles of the long-term run. Blue and orange data near zero strain are the strain data from the reference samples. All other data (between ~500 - ~3500 micro strain range) are for the large samples.

The strain data presented here are the strain values calculated from the strain gage output voltage with the constant gage factor of 2, which are considered “raw” data. There are 3 factors to be considered to calculate the true strain value due to the mechanical loading on the test section from the raw data, which are:

1. Apparent strain that is thermally induced in the KHCR strain gage as a function of the temperature,
2. Thermal expansion coefficient mismatch between the gage material and the sample,
3. Temperature dependence of the gage factor.

The apparent strain, which is thermally induced in the KHCR strain gage, is a function of the temperature and is provided in the datasheet.

Although the KHCR gages we purchased were specifically fabricated to match their thermal expansion coefficient to that of a stainless steel, in practice, it is not possible to exactly match the thermal expansion coefficient of two different materials (the strain gage element alloy and the stainless steel test section in this case) over the wide temperature. This thermal expansion mismatch produces some strain. This strain is not due to the actual mechanical tension and must be subtracted from the raw data. For the purpose to obtain the strain purely due to the thermal expansion mismatch, the two reference samples were used.

The gage factor for the KHCR strain gages is a function of the temperature and the details are provided in the datasheet.

Therefore, the strain purely due to the mechanical loading (ϵ_{cor} or corrected strain) must be obtained from the raw data as:

$$\epsilon_{\text{cor}} = [\epsilon_{\text{raw}} - \epsilon_c(T)] \times \frac{2}{K(T)} - \epsilon_{\text{ref}}(T)$$

where

$$\epsilon_{\text{ref}}(T) = [\epsilon_{\text{rr}} - \epsilon_c(T)] \times \frac{2}{K(T)}.$$

Here, ϵ_{cor} is the corrected strain, ϵ_{raw} is the raw strain data, $\epsilon_c(T)$ is the apparent strain, $K(T)$ is the gage factor as a function of temperature, $\epsilon_{\text{ref}}(T)$ is the corrected reference strain, and ϵ_{rr} is the raw strain data from the reference rods. To minimize the effects of the long-term drifting of the strain reading, a mathematical expression of $\epsilon_{\text{ref}}(T)$ as a function of temperature was developed using the first 10 thermal cycles worth of the data (ϵ_{rr}), see Figure 3.13. The relation for ~650+ °C to 700 °C was developed assuming a linear temperature dependency.

Figure 3.13. Obtained reference strain as a function of temperature (shown as red line).

Figure 3.14. Corrected strain over the first 302 cycles. T1 strain (gray) has gone over the range ($> \sim 16000 \mu\epsilon$).

As the run continued, the strain data from T1 started drifting, see gray line in Figure 3.14. In order to inspect the sample T1 and its gage (D668), the run was interrupted in July 2021 after 302 cycles. A visual inspection of T1 showed no apparent problems with the sample and gage. However, checking the various resistance values in the strain gage showed that it was most likely that the resistance of the active element has increased by about 2 Ohm (the nominal resistance of the element is 120 Ohm) and the element might have been plastically stretched. The strain gage was replaced with a new gage (D629) and the run was restarted. All other samples showed no abnormal behaviors after 302 cycles. The KHCR gages seem to be more reliable compared to the previous strain gages, as all the previous strain gages failed by 154 cycles.

The run continues as of 09/07/2021 (~ 480 thermal cycles). The entire temperature history of the run is shown in Figure 3.15. Two temperature histories during a 1000 minutes period at the beginning of the run and near 09/07/2021 are compared in Figure 3.16, indicating that the furnace has been providing consistent thermal cycle of roughly 1 cycle per 200 minutes.

Figure 3.15. Temperature history of the run up to 09/07/2021.

Figure 3.16. Temperature histories of a 1000 minute period at the beginning and near 09/07/2021.

The entire history of the corrected strain over the run is shown in Figure 3.17. The figure shows that the strain change in the order of 1000 $\mu\epsilon$ over the temperature cycle between 500 °C and 650+ °C has been achieved. As mentioned earlier, the gray line drifting away was due to prematurely failing strain gage and the new gage was installed after ~115000 minutes (approximately 80 days). Two corrected strain histories during a 1000 minutes period at the beginning of the run and near 09/07/2021 are compared in Figure 3.18, indicating that most of the amplitude of the strains over the temperature cycle have reduced. An additional comparison before and after the interruption of the thermal cycling (Figure 3.19) seems to indicate that the reduction of the amplitude of the strains over the temperature cycle has been gradual and the interruption of the cycle (cooling down to the room temperature) did not seem to significantly affect the behavior of the strain gage readings.

Figure 3.17. Corrected strain history of the run up to 09/07/2021. Plot deliberately cuts off the T1 strain reading caused by the faulty gage.

Figure 3.18. Corrected strain histories of a 1000 minute period at the beginning and near 09/07/2021.

Figure 3.19. Corrected strain histories of a 1000 minute period immediately before and after the interruption.

Finally, the relationships between the corrected strains and the corresponding sample temperatures were plotted in Figure 3.20 and Figure 3.21. The strain data from T2, which showed the largest reduction in the amplitude of the strain change over the temperature cycle, were plotted in Figure 3.22. The left figure shows the entire history of the strain, whereas the middle figure shows the 5 cycles from the 1000 minutes mark (which corresponds to the left figure shown in Figure 3.18), and the right figure shows the 5 cycles from the 15100 minutes mark (which corresponds to the right figure shown in Figure 3.18), clearly indicating the reduction of the amplitude of the strain change over the thermal cycle.

Figure 3.20. Relationship between the corrected strain and the temperature. Early T1 data (from D668 gage) were removed.

Figure 3.21. Relationship between the corrected strain and the temperature from 400 °C and 700 °C. Early T1 data (from D668 gage) were removed.

Figure 3.22. Relationship between the corrected strain from T2 and the temperature from 400 °C and 700 °C. As the run progresses, the amplitude of the strain change over the temperature change between 500 °C and ~670 °C has noticeably reduced.

3.4 Analysis and conclusions

1. The second family test articles successfully produce a larger strain change over the similar temperature cycle (order of 1000 $\mu\epsilon$ between 500 °C and 650+ °C), at least at the beginning of the thermal cycle, when compared with those of the first family test articles (order of 100 $\mu\epsilon$ between 600 °C and 700 °C).
2. The observed strain amplitude seems to reduce with repeated cycling.
3. The new strain gages (Kyowa KHCR series) have successfully operated through more thermal cycles compared with the previously used strain gages (Hitec Hoskins series HFH). Only one KHCR gage has failed so far.

The friction welding and the e-beam welding appeared to be holding the parts together, exhibiting no cracks or separations.

Some change in the strain range over time is expected as the samples move towards the steady cyclic response. However, the gradual reduction in the strain range over many cycles, especially demonstrated by sample T2, is not expected. The goal for these test articles is to induce failure in the test section. Under this scenario the strain range delivered to the test section and measured by the strain gages should be constant from the development of the stable cycle until the test section breaks (though the mean strain might change due to ratcheting).

There are at least three potential explanations for the observed decrease in the stable strain range:

1. The development of damage elsewhere in the test article, lessening the mechanical load delivered to the test section. The bimetallic welds are the most likely location for damage initiation outside the narrow test section. For example, degradation of the electron beam weld between the inner bar and casing would directly lead to a decrease in the strain range at the test section.
2. Degradation of the strain gages themselves. For example, the T1 strain gage did fail over the first few hundred cycles.

3. Loosening of the connection between the strain gage and the sample. Increased compliance in this connection would decrease the measured strain reading, even if the actual strain in the test section does not change.

The first potential explanation can be checked at the end of the thermal cycling experiment via destructive examination (sectioning) of the sample. The original T1 sample strain gage failed in a dramatically different manner than the observed gradual decrease in the strain range, which may suggest that explanation #2 is unlikely.

The most likely cause for the apparent decrease in the strain range is then explanation #3. Note that the strain range observed by sample T1, with a new strain gage, is much greater than the strain range observed in sample T2, with the original strain gage (Figure 3.19). As these samples are identical, this suggests the decrease in strain range has to do with the strain gage, and not the sample itself. Moreover, the decay in the strain range has not been consistent among the different large family samples, despite modeling suggesting that the differences in test article detailing should have only a very small effect on the stable strain range in the test section (see next chapter). Both these observations support the hypothesis that the observed decrease in the strain range is a measurement issue with the strain gage or the connection between the strain gage and the sample, rather than an actual decrease in real strains being delivered to the test section. Post-experiment characterization of the samples may be able to provide additional evidence supporting this theory.

4 Design Method Verification and Modeling

This chapter compares models of the test article of varying complexity to the results of the thermal cycling tests. As only the large test articles are instrumented with strain gages, this chapter focuses on modeling the stress/strain response of the test article in the large test articles.

We considered three analysis methods of increasing accuracy:

1. 1D, bar models with simple constitutive models used to size the gross test article geometry.
2. 2D, axisymmetric model with the same simple constitutive models.
3. Full 3D finite element analysis with a complex constitutive model designed to capture the details of high temperature cyclic plasticity in 316H and Alloy 617.

Each of these types of models serves a different purpose:

1. 1D models: validate the methods used to design the test articles by demonstrating that the actual, as measured strain range matches the design target.
2. 2D models: quantify the approximation of the bar models, which treat the smoothly-tapered inner bar (test and driver sections) as a stepped bar.
3. 3D models: quantify the effect of the geometric details and slots required to mount the strain gages, thermocouples, and provide a slot for visual inspection of the test section.

The following description refers to two different types of constitutive models:

1. “Simple models” [7]. These models capture the effect of creep and plasticity and the isotropic hardening response of Alloy 617 and 316H. However, they do not capture the full interaction of creep and plasticity nor the effect of kinematic hardening on cyclic plasticity.
2. “Complex models” [8]–[10]. These models capture the interaction of rate dependent plastic deformation and creep using a unified viscoplastic form and account for the complex effects of kinematic hardening.

The previous chapter describes the differences in the experimentally-observed strains for the different variants of the large test article geometry. All these differences are comparatively small and so this chapter uses the temperature cycle and response of the T2 bar as the reference to compare the various modeling approaches.

Figure 4.1. Stable cycle temperature history used in the simulations.

The key prediction for all modeling approaches is the time versus strain behavior of the test region of the article in stable cycle. To determine this stable strain history in the models, the simulations repeatedly impose the thermal cycle shown in Figure 4.1, keeping the entire test article isothermal. This thermal cycle is the measured temperature history for test article T1 for an arbitrary cycle (specifically cycle 100, though all cycles are nearly identical). Differential thermal expansion induces tension in the test section. The simulation monitors the strain in the test section over the 5 mm strain gage length until the simulated strains become steady over a cycle. This steady strain history may include a cycle-to-cycle increase in the net strain – i.e., ratcheting – but the strain rates over the cycle become periodic. The key result of the simulation is this stable strain range neutralized by subtracting the strain at the beginning of the cycle (so that all the strain histories start from a strain of zero and end the at the cycle-to-cycle ratcheting increment). We plot the uniaxial strain results against the cycle time, so that the times start from zero.

The strain results for sample T1 were taken from the early portion of the experiment, before the strain gage started to fail. We assume that the actual strain in the sample remains consistent and that the apparent decrease in the strain range over time for some samples is a measurement error caused by the strain gage.

4.1 1D modeling

Implementing the surveillance technology will require an accurate method to size the geometry of a test article to match the response of the corresponding structural component. A companion report describes a method for sizing the test articles using a simplified 3-bar model [4]. This method provides a fast means to size test articles by optimizing the article geometry to match a target strain

range and elastic follow up factor, describing the key details of the component creep-fatigue response, when provided with the expected test article thermal cycle and key geometric constraints on the overall size of the test article. We used a previous version of this sizing strategy, using a 4-bar model, to design the large and small test articles to hit a target strain range [5].

Validating this simplified sizing approach is one key objective of the thermal cycling experiments. Validation requires the steady-cyclic strain range in the large test articles, measured via the strain gages, to match the original, target strain range.

This sizing approach simplifies the numerical description of how the test/casing and driver materials will respond to high temperature cyclic plasticity using the simple constitutive models. Likewise, the approach simplifies the test article geometry down to the lengths and cross-sectional areas of either three or four uniaxial bars

One complication in using this simple model is how to translate the actual geometry of the test article to the simplified, 1D description. This geometric simplification neglects the effect of the slot in the casing as well as the notches required to mount the strain gages. The subsequent 2D and 3D analysis confirms that these details have little effect on the stable strain range in the test section of the sample. However, the 1D approximation also neglects the stress concentration and multiaxiality induced by the taper from the driver section to the test section in the inner bar (see Figure 4.2).

The old, 4-bar models approximate this taper region with a fourth bar in between the straight part of the test section and the driver section. The new three bar model eliminates this fourth bar to improve the performance of a numerical method for sizing the articles and to provide a further-simplified analytic solution. However, this then requires a new method for matching the tapered geometry to the 3-bar model.

Figure 4.2. Map between the test article and the 3-bar model.

Figure 4.2 illustrates the problem and our solution. We split the length of the taper between the uniaxial bars representing the test and driver sections and increase the cross-sectional area of the test section bar to account for the increase in diameter over the taper. Given the key geometric parameters used to describe the 3-bar model listed in Figure 4.2 we can describe this approach mathematically as

$$\rho_1 = \frac{r_{inner} + (r_{driver} - r_{inner})f_1}{r} \quad (4.1)$$

$$\rho_2 = \frac{r_{driver}}{r} \quad (4.2)$$

$$l_1 = \frac{L_{inner} + L_{taper}f_2}{L/2} \quad (4.3)$$

where ρ_1 , ρ_2 , and l_1 are the key, non-dimensionalized bar geometric parameters, r_{inner} , r_{driver} , L_{inner} , and L_{taper} are descriptions of the actual tapered test article geometry, and f_1 and f_2 are non-dimensionalized factors describing the map between the actual, tapered geometry and the simplified 3-bar description. Figure 4.2 illustrates all these quantities.

We consider three different maps between the actual test article geometry and the 3-bar model, described in Table 4.1. The first is an approximation based on past work and attributes 1/3 of the taper length to the test bar and increases the diameter of the inner bar (length-weighted) average diameter over that same length.

Table 4.1. Parameterized descriptions of the maps from the tapered test article geometry to the 3-bar model.

Map	f_1	f_2
Base	0.13	0.33
Best fit	0.19	0.29
Strain range	0.17	0.29

The other two maps are not *a priori* predictions of the experimental strain range, but rather *a posteriori* demonstration of how accurate the 3-bar model can be if calibrated against experimental or detailed simulation data of the test articles. These models find the coefficients f_1 and f_2 that best match the 3-bar model predictions for the stable test article strains against the experimental data for the T1 article. The “best fit” optimizes the parameters to find the map that best matches the least-squares difference between the time versus strain curve for the stable cycle from the experiment versus the time versus strain curve predicted by the model. The “strain range” option finds the coefficients that best matches the predicted model stable strain range against the experimental strain range.

Figure 4.3. Comparison between the experimental stable cycle strains and the variants of the 3-bar model.

Figure 4.3 plots the 3-bar model predicted stable strain versus time curve against the experimental data. All three models are accurate, with the optimized models naturally having better accuracy than the *a priori*, base map prediction. Table 4.2 then compares the predicted stable strain range for the three variants of the 3-bar model, the original 4-bar model prediction (which was the basis for the geometric design of the large test articles), and the experimental strain range for the T1 article.

Table 4.2. Accuracy of the simplified sizing models versus the actual experimental data.

Source	Strain range
Experiment	0.006
Original 4-bar	0.007
3-bar, base map	0.008
3-bar, best match	0.006
3-bar, strain range	0.005

The key conclusion of the 1D modeling work is that the 3-bar (and original 4-bar) models all accurately predict the experimental, measured strain range. This result validates the sizing approaches developed in the companion report [4]. An accurate sizing approach is a key component of the overall materials surveillance technology and so this validation experiment is a key step in completing the technical basis underlying the approach.

While all variants of the bar model are sufficiently accurate given the experimental uncertainty, tuning the map between the actual test article dimensions and the 3-bar model could improve the accuracy of the sizing model predictions. The parameters describing the map could be optimized in much the same way as described here using either the result of multiple experiments on differently-sized test articles or full 3D modeling of several different test article sizes in order to better sample the range of test articles that may be used in future surveillance programs. Given the objectives for the sizing model, the “strain range” optimization objective is the correct target.

Strictly, the sizing tool requires the inverse map of the one described here. That is, the sizing tool needs to translate the 3-bar dimensions to the full sample dimensions. The map here can be inverted to give the gross test article dimensions. Fully-detailing the article however requires the specific details of the taper, notches, and slots. Axisymmetric and 3D modeling can examine the effect of these details.

4.2 2D axisymmetric modeling

The first extension of the 1D bar models is to represent the test article geometry with a 2D, axisymmetric model. Figure 4.4 shows an axisymmetric model of the large article. This model accounts for the taper between the test and driver sections, but still neglects the strain gage notch and the slot in the casing. We ran a steady cyclic analysis of the strain in the test section using the approach outlined above. This analysis used the “simple” material models for both 316H and Alloy 617. The model assumes a complete weld between the test and driver bars (stir friction weld) and a 0.5 in. weld depth penetration between the inner bar and the casing (electron beam weld).

Figure 4.4. Axisymmetric model of the large test article. The colors show the three different sections.

Figure 4.5 plots the strain versus time profile for the steady cyclic limit compared to the experimental data. The model is as accurate as the best 1D bar models for the strain range but also better-captures the experimental strain versus time profile. The conclusion from this simulation is that while including the details of the taper can and does improve the model accuracy in terms of the strain versus time prediction, it does not significantly improve the accuracy of the strain range prediction. As such, the 1D bar model is sufficiently accurate to design the test article geometry.

Figure 4.5. Comparison between the experimental data and the axisymmetric model.

4.3 Full 3D modeling

Full 3D analysis is the logical extension of the test article simulations. A full 3D analysis captures all the geometric details of the actual, large test articles including the taper, notch, and slot features. These simulations also apply more complex constitutive models to capture the details of coupled creep and plasticity and kinematic hardening in the test article.

The 3D analysis can then examine the differences between the three different large sample geometries (taper and slot, step and slot, and taper without slot). The analysis was conducted through FEA software ANSYS, and sample geometries were built up using ANSYS SpaceClaim, based on STEP files describing the test article geometry. The temperature profiles were applied at the surface of the samples, based on the measured data. After temperature fields were determined at each time spot during the thermal cycle transient in the heat transfer model, the temperature results were loaded into structural model to calculate stresses and strains. This analysis uses the “complex” material models.

Each sample geometry consists of the case, which is the same for all the three geometries, a rod made of Alloy 617 rod, a 316H transition and a 316H rod attached to the strain gage. Due to symmetry, only a quarter of each geometry was included in the FEA models.

The meshes on the cases and the Alloy 617 rods are coarse (~2mm in size), as they are just transfer the load, while the meshes at the SS316 rod for strain measurement are fine, about 1mm in size,

and the mesh size in the transitions is 1.5mm. The meshes for the three sample geometries are shown in Figure 4.6.

Figure 4.6. Meshes for the (a) taper with slot (TS), (b) the step with slot (SS), and (c) the taper without slot (T) geometries.

The mechanical loads are driven by the difference of thermal expansion coefficients between Alloy 617 and SS316, there are two symmetric planes along the X and Y directions, due to the geometry symmetry and the center point of one end is fix in Z direction. Figure 4.7 shows the boundary conditions for the TS sample, those for SS and T samples are similar.

Figure 4.7. Mechanical boundary conditions in the 3D models.

As the thermal ramping rate is small, less than $4^{\circ}\text{C}/\text{min}$, we assumed a fixed-temperature load at the sample surface. The surface for the thermal load is shown in Figure 4.8 below for the TS sample (the surfaces with thermal load are shown in red), and the thermal loads for SS and T samples are similar. We also assume the thermal transients are the same for the three samples, even though they were at different locations inside the furnace for easier comparison.

Figure 4.8. Sample thermal boundary conditions.

Figure 4.9 plots the stable strain versus time results from the simulations along with the experimental data for the T1 sample. The 3D analysis with the full viscoplastic constitutive models is, unsurprisingly, the most accurate modeling approach for capturing both the strain range and the details of the strain versus time profile.

There are only very small differences between the simulated strain profiles for the three test article geometries. This result suggests that capturing these details is not important, particularly when sizing test articles to match a target strain range.

Figure 4.9. Comparison between the 3D simulation results and the experimental strain gage measurements for the stable cycle.

4.4 Summary of modeling work

Figure 4.10 summarizes the models described in this chapter by plotting the predictions for the stable cycle strains versus the experimental results. This figure replots results shown in Figure 4.3, Figure 4.5, and Figure 4.9 above. While the different geometric and material model choices do affect the simulated results, all the model predictions fall within a fairly narrow range and close to the measured strain data.

The key results of the modeling study described here are:

- The thermal cycle test results validate the 1D, 3-bar model used to size the test articles to match the key mechanical response of a component.
- The strain range predictions are robust against differences in the material constitutive response. Both the simple and more complex models adequately predict the experimental results.
- While the geometric details (the taper, notches, and slots) do affect the predicted cyclic strains, these differences are comparatively small and can be neglected in predicting the steady cyclic strains.

Figure 4.10. Summary plot comparing all the simulation results to the experimental data.

5 Conclusions

5.1 Summary of this report

This report describes the design, fabrication, and testing of a family of passively-actuated materials surveillance test articles that impose cyclic, creep-fatigue type loading on a test section driven only by temperature variations via differential thermal expansion. Test articles of this type are a key enabler for the surrogate materials surveillance technology being developed by the Advanced Reactor Technologies Program, as they can be used to impose realistic mechanical load *in situ*, using only the normal variation in the reactor temperature caused by operating load cycles.

The key results demonstrated in this report are:

- The basic test article described here can be successfully fabricated and the fabrication process can produce realistically-sized surveillance test articles.
- The four bimetallic joints in the test articles are sufficiently strong to survive repeated thermal cycling.
- The test results validate the 1D sizing model described in a companion report [4]. This sizing approach is another key ingredient for future material surveillance programs, as it provides a means to design test articles to match the key mechanical response of an operating component, given the thermal cycle as input.
- More detailed modeling suggests that while the various test article geometric details developed here do affect the strain delivered to the test section, these variations are comparatively small and could be neglected in sizing test articles.

5.2 Future work

The work here, together with the companion report [4], validates the basic materials surveillance concept using the test articles described here. Future work could further optimize the test article design as we as improve the accuracy of the sizing models by:

- Improving the map between the full 3D test article geometry and the 1D model, either through further full 3D simulations or additional tests.
- Continuing the thermal cycling tests to failure, to ensure that failure occurs in the test section and not elsewhere, like in the bimetallic welds. Similarly, post-experiment characterization could verify the hypothesis that the decrease in the strain range for some articles is measurement error caused by the strain gage and not a real degradation in the load being delivered to the test section.
- Additional instrumented tests on different-sized test articles, to further validate the sizing procedure.

Additional testing will be required to demonstrate the concept before it can be used in a future operating reactor. Future tests might include:

- Longer-term cyclic tests aimed at evaluating smaller, realistically sized test articles under realistic loading conditions. Ideally these tests would continue until the test article fails, though some tradeoff between strain range and test time would need to be considered.
- Environmental testing, to ensure the test articles remain robust when exposed to molten salt. These tests would need to demonstrate the basic function of the test article, for example making sure the welds remain robust when exposed to salt, as well as some of the functional aspects of the test articles, like making sure salt flows past the test section through the slots in the casing, rather than stagnating.

Finally, additional work may be required to reduce further the size of the test articles. The current small article family has an outer envelope of a 3 in. tall, 1 in. diameter cylinder. Further miniaturization would make it easier to locate more samples in the reactor and reduce the impact of maintaining the test articles during plant operation.

5.3 Refractory weld tests

One key result of the companion report [4] is that the difference in the coefficient of thermal expansion between the test/casing and driver materials limits the test article design. For fixed geometry, the larger the CTE mismatch the larger the strain range delivered to the test section or, conversely, for a fixed strain range the larger the CTE mismatch the smaller the required test article envelope. Increasing the CTE mismatch is then one potential means to minimizing the test article volume while retaining a good range of achievable strains.

For many materials, a tensile hold during creep-fatigue is more damaging than a compressive hold. A surveillance program would then likely want to deliver tensile loading to an *in situ* surveillance article. The current test article designs deliver tension to the test region if the driver material has a lower CTE than the test material. Increasing the CTE mismatch then requires finding a low CTE driver material.

Most low CTE materials are non-metals, which would present a challenge in fabricating the test article. Limiting the search to metals, most low CTE materials are refractories. The most likely materials in terms of availability and creep resistance are Mo, W, or their alloys.

Fabricating a test article with a refractory driver requires joining the refractory to the test and casing material. For example, here these materials are 316H stainless steel. Applying the current fabrication process would then require both stir friction and electron beam welds between a refractory alloy and 316H stainless steel.

We have started a preliminary investigation of the viability of friction-welding to join one of the commonly available refractory metals (Titanium Zirconium Molybdenum alloy or TZM) and 316H stainless steel with American Friction Welding (AFW). TZM bars and 316H bars were machined at ANL and shipped to AFW where the friction welding developmental work was carried out (Figure 5.1). Some of the weld parameters were suggested by ANL, but the actual welding and associated developmental work were carried out by AFW. It was noted that the oxygen in the air would negatively affect the weld quality, but we agreed to perform the first weld developmental work in the air, because the significance of the oxygen on this specific welding work was unknown.

The first approach was to minimize or eliminate the negative effects of the presence of the air (oxygen) by adjusting the friction welding parameters.

Figure 5.1. Machined materials (316H and TZM) to be shipped to AFW for friction weld development.

This preliminary study did not produce a viable set of welding parameters. Although an acceptable welding procedure could not be found, some partial bonding between TZM and 316H was obtained (Figure 5.2A). This partial bonding was actually promising given that the welding was carried out in the presence of oxygen. Various welded composite rods underwent a bending test to verify the joint strength. Because of the known brittleness of TZM, if the joint were strong, the TZM portion of the rod should break. However, if the joint quality is not sufficient, only a portion of the TZM rod remains on the mating surface of the 316H portion (Figure 5.2(A) and Figure 5.2(B)) or the TZM rod completely comes apart and away from the 316H rod (Figure 5.2(C)).

Figure 5.2. (A) Partial, but best welding between TZM and 316H. (B) Partial bonding, and (C) no bonding. Note that the welded composite bars shown in the photo underwent a quick bending test to verify the joint strength.

The preliminary welding results indicated that the center area, which was least affected by the air, seemed to exhibit a relatively good bonding. Installing a shielding device around the weld area to keep the air away will most likely improve the weld quality, possibly to a point that the weld strength is sufficient for the tensile strength test. Completion of this development of the weld technique between a refractory alloy and 316H would significantly expands the applicability of this passively actuated creep-fatigue test concept by reducing the test article size and producing

more tension in the samples, which would allow the fabrication of a miniaturized samples that can actually be placed in a reactor environment.

A shielding device was designed to minimize the exposure of the weld area to the air, see Figure 5.3. This cover is to be placed over the stationary rod with an outer diameter of 0.75 inches and is long enough to extend over where the friction welding takes place. The 1/4 inches tube will be connected to an argon supply to keep the weld area from the surrounding air.

Figure 5.3. The drawing of the shielding gas cover.

This shielding cover is being fabricated at ANL and the additional TZM and 316 rods are also being prepared at ANL. Once they are ready, they will be shipped to AFW for the next weld development trial, likely in FY22.

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Applied Materials Division

Argonne National Laboratory
9700 South Cass Avenue, Bldg. 212
Argonne, IL 60439

www.anl.gov

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