INL/EXT-18-44376-Revision-0

Quarterly Management Document – FY18, 1st Quarter, Physics-based Creep Simulations of Thick Section Welds in High Temperature and Pressure Applications

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January 2018

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Quarterly Management Document – FY18, 1st Quarter, Physics-based Creep Simulations of Thick Section Welds in High Temperature and Pressure Applications

Document # INL/EXT-18-44376

WBS Element	Project Title	Contract Number	Contract Start	Contract End
C.B.10.02.02.40	Physics-based Creep Simulations of Thick Section Welds in High Temperature and Pressure Applications	FEAA90	10/01/17	09/30/2018

Performer Name and Address	Principal Investigator(s)
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BUDGET AND COST REPORT

Prior Year Funds ($K)	**230**
Total Current Year Commitment ($K)	**0**
Projected Current Year Costs ($K)	**230**

	O	N	D	J	F	M	A	M	J	J	A	S
Monthly Planned Costs	**16**	**15**	**16**	**21**	**19**	**21**	**31**	**18**	**20**	**15**	**15**	**23**
Actual Monthly Costs	**26**	**17**	**9**									
Monthly Variance	**-10**	**-2**	**7**									
Total costs – planned	**16**	**31**	**47**	**68**	**87**	**108**	**139**	**157**	**177**	**192**	**207**	**230**
Total costs - actual	**26**	**43**	**52**									

MILESTONE REPORT

Milestone Designation	Milestone Description	Due Date	Revised Due Date	Completion Date
A	Evaluate current MOOSE capabilities	09/30/2015		09/30/2015
B	Complete Alloy 617 weld characterization	10/30/2015		11/18/2015
C	Receipt of Alloy 740H plates	10/30/2015		11/05/2015
D	Complete welds in Alloy 740H	11/16/2015	7/31/2016	7/31/2016

E	Characterize Alloy 740H welds	02/01/2016	09/30/2016	9/02/2016
F	Creep model development – Stage 1	09/30/2016		9/30/2016
G	Creep Model Development – Stage 2	8/29/2017	3/30/2018	
H	Calibration of Secondary creep	9/30/2017	04/30/2018	
I	Stress Drop Tests	2/01/2017	3/30/2018	
J	Characterization of creep failure mechanisms	4/01/2017	04/30/2018	
K	Secondary creep calibration for welds	5/30/2018		
L	Creep model development – Completion of Stage 3	8/30/2018		
M	Creep simulation of a welded joint in Alloy 740H	9/30/2018		
N	Validation of creep simulation model via an Alloy 740H weld consisting of refined microstructure	9/15/2018		

TECHNICAL HIGHLIGHTS

Milestone G, "Creep Model Development – Stage 2"

Not all the objectives of this task were attained during FY17 and these remaining objectives will be finished in FY18 using carryover funds (the project was underspent in FY17). The main objective that remains is to incorporate Orowan looping and dislocation/γ' interactions into the creep model. The effect of the evolution of gamma prime size on the looping and/or dislocation interaction also will be included in the model. Preliminary calibration of the model will be conducted using the experiment data of Alloy 617. Additionally it is still necessary to translate experimental microstructures into a form that can be used in the modeling and simulation. The extent of weld makes serial sectioning with EBSD cost-prohibitive and the current approach is to characterize the microstructure in three orthogonal directions using EBSD and then using this information to generate "synthetic" microstructure, i.e. a microstructure that is representative of the actual microstructure with the same distributions in grain size, grain shape, orientation, etc. but not necessarily exactly the same as the experimental microstructure. The synthetic microstructure will be in a format appropriate for importing into the model and simulation environment. Investigators (D. Post-Guillen and T. Ashton, "Development of a Solid Texture Synthesis Algorithm from 2D Exemplars") at INL associated with other programs are also working on this problem and contact has been made to explore common interests with regard to this issue. The expected completion date for this task has been moved to the end of March 2018.

Milestone H, "Calibration of Secondary creep"

The secondary creep rate data obtained from existing creep data on Alloy 617 from the NGNP program will be used to assess the accuracy of the model and then calibrate the model. Work on this task can only start after the dislocation/γ' interaction has been incorporated into the model which is expected to be complete by mid-February. Therefore, the completion date for this task will be moved to the end of February 2018.

Milestone I, "Stress Drop Tests"

This task also was not completed during FY17 as originally planned due to the long duration of these tests, which are needed to quantify the creep strengthening associated with dislocation interactions with the γ' particle distributions at various temperatures and various γ' particle sizes. Specifically, the test is designed to measure the threshold stress required for dislocations to pass through the γ' particle dispersion. One test has been completed (Sample ID 740-SD-01-01, 750°C) while three more are in progress (740-SD-01-02, 740-SD-01-03 and 740-SD-0-01), Table 1. An example of the creep curve associated with the stress drop test is shown in Figure **1**. After the sample enters secondary creep the load is reduced. After the stress drop, there is a transient period where the sample does not creep. The time elapsed until the sample starts to creep again is used to determine the threshold stress according to the following the equation:

$$\sum \Delta t = K((\sigma_R - \sigma_T)^{-2} - (\sigma_i - \sigma_T)^{-2}) \qquad \text{Eqn. 1}$$

where

- $\sum \Delta t$ is the summation of the elapsed times from previous stress drops
- K is a kinetic constant
- σ_R is the remaining stress after the stress drop
- σ_T is the threshold stress (the unknown)
- σ_i is the initial stress at the start of the test

The equation is non-linear and a non-linear solver is used to determine both K and σ_T. Test 740-SD-01-01 at 750°C and an initial stress of 305 MPa was completed during the 1st quarter of FY18 and the determination of the threshold stress performed. The analysis yielded a threshold stress of about 67 MPa at this temperature. This seems somewhat low since a previous project on Alloy 617, with a much lower γ' particle fraction (<5% vs. ~20% for Alloy 740H) found a threshold stress of 77 MPa. However, it is not known at this time whether the γ' particle size was larger than that in the Alloy 617 test, which could possibly account for the lower threshold stress in Alloy 740H at this temperature. An alternate method (the Lagneborg–Bergman analysis of minimum creep rates, Met. Sci., 1976, vol. 10, pp. 20–28) for determining the threshold stress value from the existing stress drop data will be performed in the next quarter to verify the result found here by the Henderson-McLean method, (P.J. Henderson and M. McLean: Acta Metall., 1983, vol. 31, pp. 1203–19).

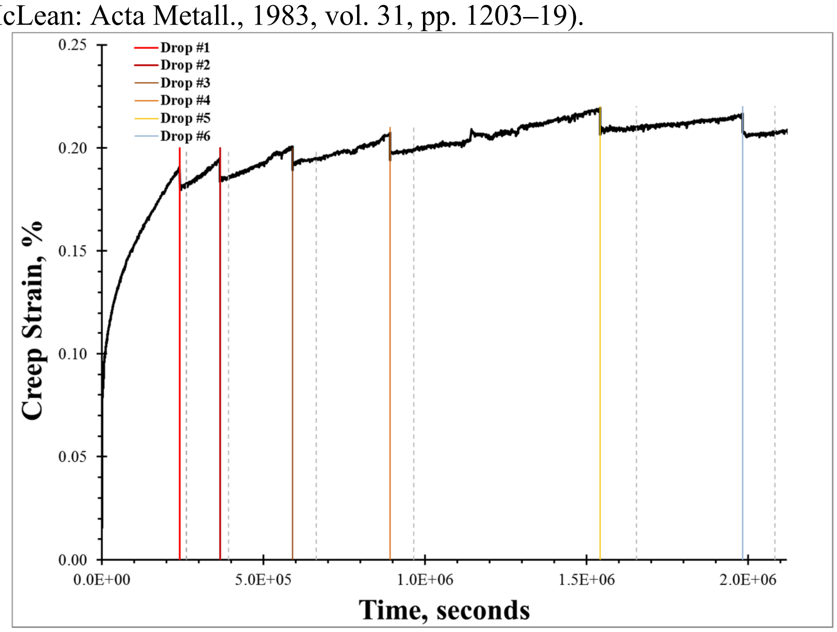

Figure 1. Creep curve for the stress drop test associated with sample 740-SD-01-03. The stress is periodically drop after the creep curve enters secondary creep. The time elapsed until the sample starts to creep again is used to determine the threshold stress.

Table 1. Conditions for Threshold Stress Determination – Stress Drop Tests

Sample ID	Test Temperature, °C	Material Condition	Initial Stress, MPa	Objective
	700	As-received	413	For threshold stress - γ' size A
740-SD-01-02	700	Aged, 750°C, 4003.8 hrs	413	For threshold stress- γ' size B
	700	Aged, 750°C, 8000 hrs	413	For threshold stress- γ' size C
740-SD-0-01	750	As-received	305	For threshold stress- γ' size A
740-SD-01-01	750	Aged, 750°C, 4003.8 hrs	305	For threshold stress- γ' size B
	750	Aged, 750°C, 8000 hrs	305	For threshold stress- γ' size C
	800	As-received	200	For threshold stress- γ' size A
740-SD-01-03	800	Aged, 750°C, 4003.8 hrs	200	For threshold stress- γ' size B
	800	Aged, 750°C, 8000 hrs	200	For threshold stress- γ' size C

Milestone J, "Characterization of creep failure mechanisms"

As of the end of the third quarter, nine creep tests have been completed. They have been mounted and polished. Characterization of these samples using optical metallography and SEM, including orientation imaging microscopy (OIM), is in the initial stages and is not complete at this time. This will require this task to be carried over to FY18 and the planned completion date for this task be moved to the beginning of March. This carryover workscope will be performed with the carryover funds from FY17.

Milestone K, "Secondary creep calibration for welds"

The simulated secondary creep rates in welds of Alloy 617 will be calibrated using existing creep data for welds in that alloy. However, this task is dependent on completion of the tasks outlined in Milestone G. Therefore, this task will not start until the 2nd quarter.

Milestone L, "Creep model development – Completion of Stage 3"

This is the last stage in the development of the creep simulation. The evolution of γ' particles during the creep test will be incorporated into the simulation to allow proper handling of the changing dislocation interactions as the γ' particles grow – from particle shearing to particle bypass by climb to particle bypass by dislocation looping. Again, this task cannot be started until the tasks of Milestone G have been completed.

Milestone M, "Creep simulation of a welded joint in Alloy 740H"

This task will not start until after the model has been calibrated and verified with the existing creep data on welds in Alloy 617 and various material parameters for 740H welds, including initial microstructure for a weld in Alloy 740H have been determined.

Milestone N, "Validation of creep simulation model via an Alloy 740H weld consisting of refined microstructure"

This task is designed to test/validate the model against welds with a finer grain size. The emerging technique of hybrid laser-arc welding offers the potential of greatly increased productivity with an additional decrease in the grain size of welds. To explore the validity of the model, a state-of-the-art hybrid laser arc welding system is being prepared to weld Alloy 740H. During this quarter, existing hybrid laser arc welding equipment has been assembled and computer-controlled system checked. Trial hybrid laser arc welding runs on Alloy 740H will be performed early next quarter.

Other highlights

γ’ Aging Study

Aging of welds at 700, 750 and 800°C continues. Material aged at these temperatures for 10,000 hrs was removed during this quarter and are being prepared for analysis of the γ’ particle size distribution. TEM samples will be prepared from the base material, HAZ and weld metal and observed in the TEM at the Center for Advanced Energy Studies (CAES) in the next quarter. TEM samples of other material aged for lower durations have already been prepared by electropolishing and analyzed in the TEM. Image analysis was used to determine the γ’ size distribution and the average particle size as a function of aging time. The results for aging weld metal at 750°C have been plotted along with the γ’ particle size data for aging of Alloy 617 base metal that was obtained in a previous project. From these preliminary results it appears that the γ’ particle growth behavior is virtually the same as that found for Alloy 617 at an aging temperature of 750°C. The main difference is the size of the error bars which are considerably larger on the 740H weld metal data. However, the data for Alloy 617 was obtained from base metal samples. Non-equilibrium cooling in the weld metal of Alloy 740H resulted in macro-segregation and variation in the local composition. This variation in composition likely is responsible for local variations in γ’ precipitation and growth behavior, ultimately resulting in a wider variation in γ’ particle size in weld material compared to base metal which has a more uniform composition throughout. Analysis of Alloy 740H base metal aged at 750°C will be analyzed and added to the plot of Figure **2**. The average γ’ size data for base, HAZ and weld materials aged at other temperatures and times will also be added to the plot in Figure **2** as the analyses are completed.

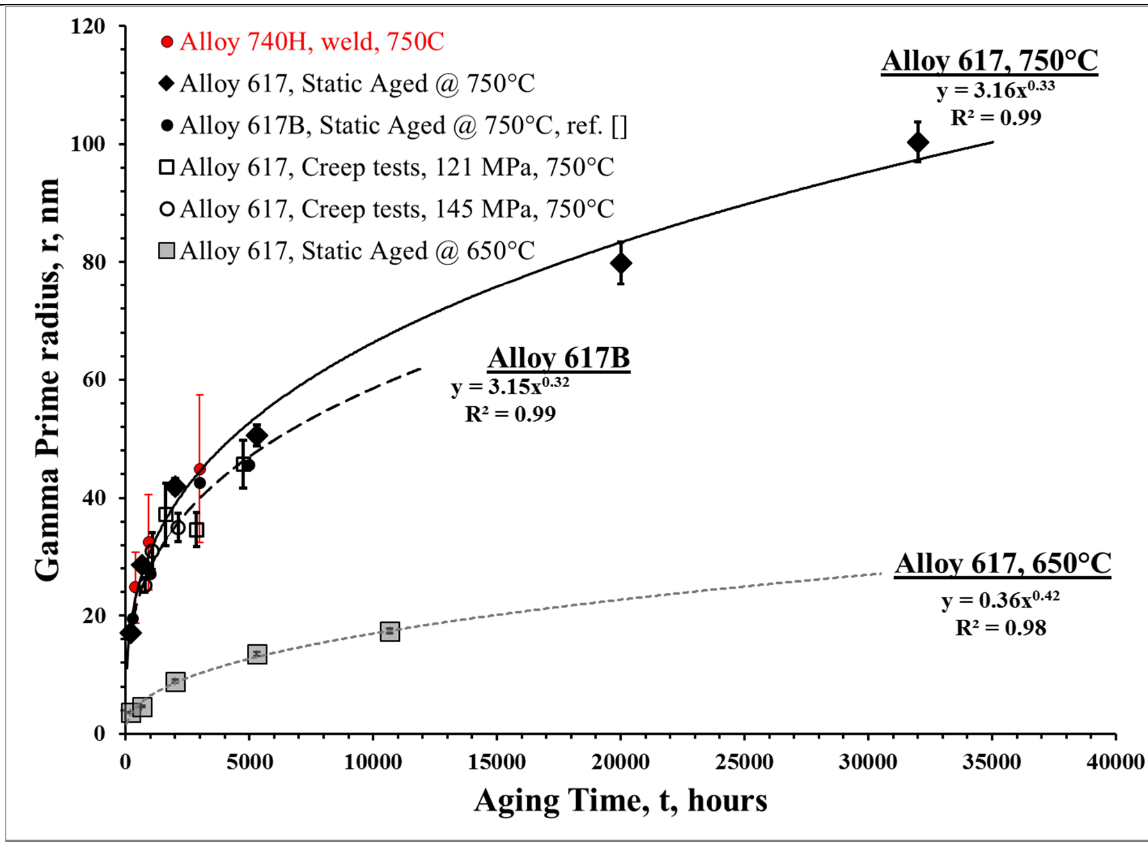

Figure 2. Growth characteristics of γ' in Alloy 740H weld metal have been plotted with γ' growth behavior found in the base metal of Alloy 617. Aging temperature for the Alloy 740H weld metal was 750°C.

ISSUES

Both the modeling effort and the experimental data acquisition and characterization fell behind schedule in FY17 and under budget. Although some ground was made up during the first quarter of FY18 the project remains behind schedule but the remaining funds still appear to be sufficient to complete the remaining tasks.

Report Prepared By	Date
Thomas M. Lillo	01/23/2018