Transactions, **SMiRT-22**
San Francisco, California, USA - August 18-23, 2013
Division VIII

PREDICTION OF THE CREEP-FATIGUE LIFETIME OF ALLOY 617: AN APPLICATION OF NON-DESTRUCTIVE EVALUATION AND INFORMATION INTEGRATION

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ABSTRACT. A relatively simple method using the nominal constant average stress information and the creep rupture model is developed to predict the creep-fatigue lifetime of Alloy 617, in terms of time to rupture. The nominal constant average stress is computed using the stress relaxation curve. The predicted time to rupture can be converted to number of cycles to failure using the strain range, the strain rate during each cycle, and the hold time information. The predicted creep-fatigue lifetime is validated against the experimental measurements of the creep-fatigue lifetime collected using conventional laboratory creep-fatigue tests. High temperature creep-fatigue tests of Alloy 617 were conducted in air at 950°C with a tensile hold period of up to 1800s in a cycle at total strain ranges of 0.3% and 0.6%. It was observed that the proposed method is conservative in that the predicted lifetime is less than the experimentally determined values. The approach would be relevant to calculate the remaining useful life to a component like a steam generator that might fail by the creep-fatigue mechanism.

INTRODUCTION

Changes in operating conditions during the reactor start-ups and shutdowns or during period of service will result in transients. If these transients are repeated during the component life, it will produce low cycle fatigue loadings of components. In addition, stresses during steady power operation induce creep damage. The combined effect results in a creep-fatigue interaction, which is usually the main failure mode in high temperature materials.

Carroll et al. [2011] presented the study on the creep-fatigue interaction of nickel-based material, Alloy 617 in air at 950°C. Alloy 617 is the leading candidate material for Intermediate Heat eXchanger (IHX) in a helium-cooled very high temperature reactor (VHTR) system and was tested at Idaho National Laboratory (INL) to address the needs for codification and licensing [Carroll et al., 2011]. In this paper, the available creep-fatigue behavior experimental measurements of Alloy 617 and the stress relaxation curves for different tensile hold periods (up to 1800s) in a cycle are utilized to validate and predict the creep-fatigue lifetime of Alloy 617 respectively.

The creep-fatigue lifetime prediction study was performed as part of the Instrumentation, Information, and Control Systems (II&C) technologies pathway's *centralized online monitoring research* [Agarwal et al., 2012]. The II&C is one of the pathways under the Light Water Reactor Sustainability (LWRS) Program sponsored by the U.S. Department of Energy, Office of Nuclear Energy. Other pathways include [INL/EXT-11-23452]: Material Aging and Degradation (MAaD), Advanced Light Water Reactor Nuclear Fuels, and Risk-Informed Safety Margin Characterization.

The methodology presented in this paper to predict the creep-fatigue lifetime of Alloy 617 is a demonstrative exercise that would be relevant to calculating the remaining useful life (RUL) of a component like steam generator that might fail by the creep-fatigue mechanism. This exercise is in-line with one of the research objectives of the MAaD pathway, i.e., performing passive structure health assessment and its RUL estimation online using advances in non-destructive evaluation (NDE) techniques and prognostic models (currently researched under the II&C pathway) respectively.

At present, material aging and degradation analysis is performed via in-service inspection utilizing NDE techniques during plant outage that is a time consuming and an inefficient practice. The most commonly used method for analyzing creep-fatigue data is the time fraction approach, as described in the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code for example. This approach partitions the damage from creep and from fatigue individually and sums these individual contributions to approximate the total damage. The creep contribution is calculated in a manner similar to that presented here. In the more general case discussed in the ASME Code fatigue can be an important damage mechanism. The time fraction approach is a continuum level description that does not reflect the underlying failure mechanism. The approach described in this paper for creep-fatigue of Alloy 617 at 950°C is informed by microstructural analysis where it has been determined that fatigue does not play a significant role in determining the cycles to failure, which allows the simplified method described here to be applied.

The paper is organized as follows: Creep-fatigue deformation of Alloy 617 is discussed next, followed by the prediction of the creep-fatigue lifetime of Alloy 617 using a relatively simple method. Finally, conclusions and future research are presented.

CREEP-FATIGUE DEFORMATION

In this section, the experimental outcomes of the creep-fatigue deformation of Alloy 617 performed at INL are summarized [Carroll, 2011, one more ref.]. A critical component in the VHTR system for extracting thermal energy at maximum expected outlet temperature of 950°C is the IHX. Creep-fatigue deformation is expected to be the primary damage mode for IHX occurring during reactor start-ups and shut-downs or power transients during normal operation. Alloy 617 is the leading candidate material for IHX in a helium-cooled VHTR system and was tested at INL to address the needs for codification and licensing. Low cycle fatigue (LCF) and creep-fatigue testing were conducted [Carroll et al., 2011] in accordance with the American Society of Testing and Materials (ASTM) Standard E606-04 [ASTM, 2004]. For details on the experimental setup and procedures followed, refer [Carroll et al., 2011].

To approximate the expected deformation mode in a laboratory setting, creep-fatigue test introduces a hold time up to 1800 seconds during the tensile portion of a strain-controlled fatigue cycle. The ramp rate of 10^{-3}/s is maintained during the creep-fatigue testing. During the tensile hold, time dependent creep deformation can occur. A schematic creep-fatigue test cycle is shown in Figure 1. The experimental measurements for tensile hold of 180 and 1800 seconds at 0.3% and 0.6% total strain are listed in Table 1.

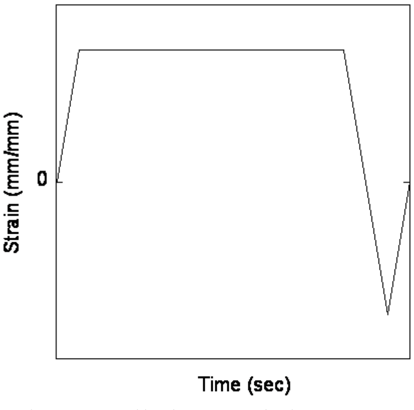

Figure 1. Schematic of a strain controlled creep-fatigue test cycle with tensile hold time.

Table 1. Creep-fatigue tests completed at 950°C and a strain rate of 10^{-3}/s [Carroll et al., 2011].

Strain Range (%)	Hold time (seconds)	Cycles to failure
0.3	180	2485
	1800	4650
0.6	180	950
	1800	661

One of the main conclusions from these studies was that the introduction of a hold time at the peak tensile strain decreased the number of cycles to failure. The results of these experiments are shown in Figure 2. Lines are shown on the plot but are not meant to accurately capture the trend with hold time. Increasing the duration of the hold from 180 to 1800 seconds did not significantly reduce the cycle life, indicating that the number of cycles to failure in creep-fatigue reaches saturation and is independent of increasing hold time [Carroll et al., 2011].

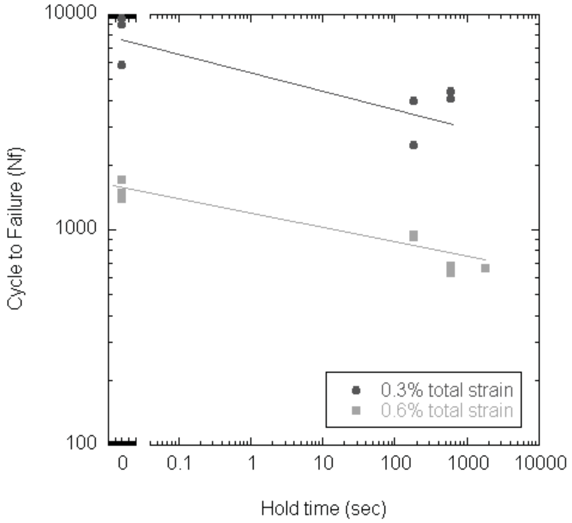

Figure 2. Number of cycles to failure in low cycle fatigue and creep-fatigue of Alloy 617 as a function of the tensile hold time [Carroll et al., 2010].

Creep-fatigue interactions are often depicted microstructurally in stainless steels, for example, as the combined effects of fatigue damage and creep damage. The fatigue component is considered to be the initiation and propagation of surface cracks, while the creep component is manifested as creep voids or cracking on interior grain boundaries (or wedge cracking at triple junctions), each of which develop independently. Linking these two deformation modes results in accelerated failure compared to fatigue alone. Metallographic analysis of Alloy 617 creep-fatigue specimens at 950°C showed populations of fine intergranular cracks in the interiors of the specimens that were associated with creep deformation. This type of intergranular cracking is shown in an optical micrograph in Figure 3. The amount of intergranular cracking increased with increasing tensile hold time. Short cracks that initiated at the specimen surface associated with grain boundary oxidation during the extended exposure to elevated temperature during a creep-fatigue test were observed. These surface cracks did not grow appreciably until very near the end of specimen life. It was thus concluded for Alloy 617 that, unlike stainless steels, at high temperature the cycles to failure in creep-fatigue is determined largely by the creep behavior of the material and the fatigue contribution is negligible.

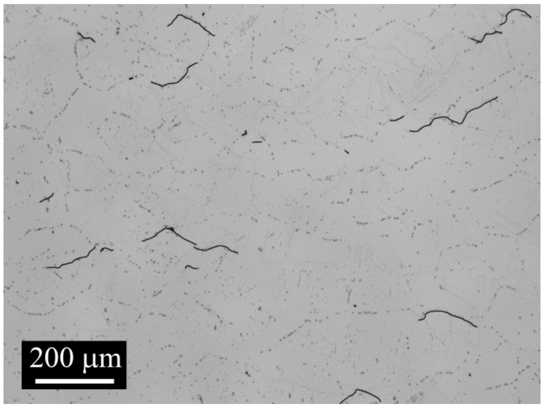

Figure 3. Optical micrograph of a cross section through the gage section of a creep fatigue specimen showing inter-granular cracking associated with creep deformation [Carroll et al., 2010].

PREDICTION OF CREEP-FATIGUE LIFETIME

Understanding that creep-fatigue failure is dominated by the creep behavior of the alloy suggests a method for predicting creep-fatigue life. By knowing the strain rate and hold time during creep-fatigue testing, converting the cycles to failure in Figure 2 into time to failure is straightforward. Literature has extensive historical data describing the time to failure for Alloy 617 in creep as a function of the applied stress. Time to rupture data for Alloy 617 at 950°C is shown in Figure 4. If the stress history of the creep-fatigue specimen is known, the data in Figure 4 can be used to approximate the time to failure.

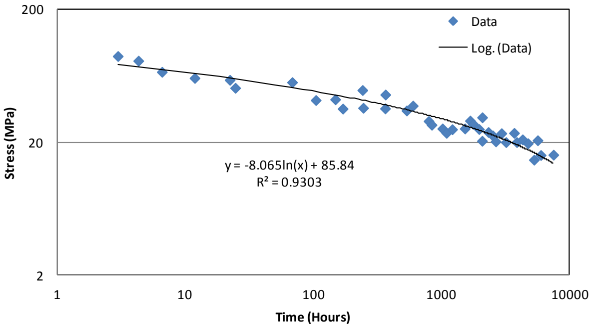

Figure 4. Time to rupture data and a mathematical fit to the data as a function of applied stress for Alloy 617 at 950°C.

Cyclic stress-strain data are available for each creep-fatigue specimen for each loading cycle. The tests are strain controlled, thus during the tensile hold time stress relaxes rapidly from the peak value. Stress as a function of tensile hold time (a stress relaxation curve) is shown in Figure 5, where the stress quickly relaxes to a constant value, regardless of the peak stress value. Having the stress relaxation curve shown in Figure 5 and knowing the peak stress and the duration of the tensile hold time it is possible to calculate an average stress on the sample for each cycle. Calculated average stresses as a function of creep-fatigue cycle are shown in Figure 6 for tensile hold time of 180 and 1800 seconds. As shown in Figure 6, the average stress during the tensile hold reaches a nearly constant value after about 10 cycles and does not decrease significantly until bulk cracking occurs at about 10^3 cycles. Initiation of bulk cracking would be the point at which the component could be considered to have failed for a service failure.

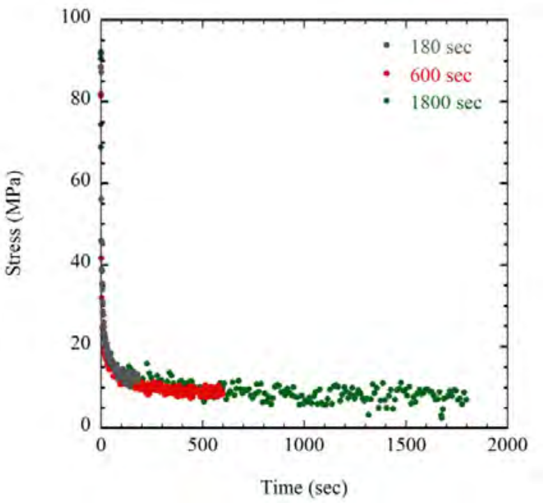

Figure 5. Stress relaxation behavior of Alloy 617 at 950°C for different tensile hold time.

Using the nominally constant average stress, the time to rupture can be determined from Figure 4, which can easily be converted to number of cycles using the strain range, the strain rate during that cycle, and the hold time. This was done for two specific specimens with a total strain range of 0.3% and hold times of 180 and 1800 seconds. The predicted cycles to crack initiation using this method for the 180 seconds hold is 2274 cycles compared to experimentally determined value of 2485 cycles. The predicted cycles to crack initiation for the 1800 seconds hold is 4279 cycles compared to the experimentally determined value of 4650 cycles.

Both of the cycles to failure values calculated with the simple creep rupture method are conservative in that they are slightly less than the experimentally determined values (within 10% of the experimental value). The advantage of this method is that it allows prediction of cycles to failure for conditions that have not been characterized with data from on the order of 10 experimental cycles, rather than carrying out full tests that can take up to a month for some conditions. In addition through this simple modeling approach it was discovered that there are fatigue-induced changes in the elastic properties that correlate with lifetime. The elastic properties can be measured using non-contacting, laser-based ultrasonic methods. Thus the analysis not only allows lifetime prediction, but leads to the suggestion of a specific NDE method, which could form the basis for OLM of materials degradation.

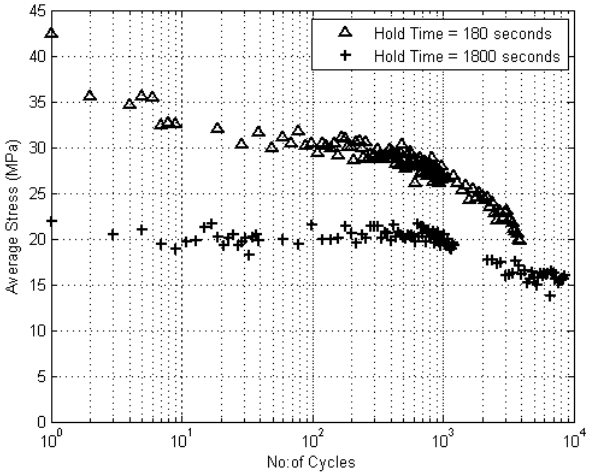

Figure 6. Average stress per cycle for 180s and 1800s hold time under 0.3% total strain.

CONCLUSIONS AND FUTURE RESEARCH

The three main conclusions reported in the paper are: (1) A simple model to predict creep-fatigue lifetime of Alloy 617 and to characterize high temperature degradation of Alloy 617 was presented. Results are validated using the experimental measurements of the creep-fatigue lifetime collected using conventional laboratory tests. The predicted creep-fatigue lifetime is conservative in that they are slightly less than the experimentally determined values. (2) For Alloy 617 at high temperature the cycles to failure due to creep-fatigue mechanism is determined largely by the creep behavior of the material and the fatigue contribution is negligible. (3) Increasing the duration of the tensile hold time from 180 to 1800 seconds did not significantly reduce the cycle life of Alloy 617, indicating that the number of cycles to failure in creep-fatigue possibly reaches saturation and is independent of increasing hold time.

The next path forward would be to develop a prognostic method for systems where creep-fatigue at high temperature is the dominant failure mechanism. One of the possible approaches includes developing a non-contacting laser-based system to measure Young's modulus of a material undergoing creep-fatigue damage. The modulus is indicative of the amount of accumulated damage in the material. By knowing the time to rupture behavior of the material, it will be possible to develop a prognostics algorithm for predicting remaining lifetime for the material.

ACKNOWLEDGEMENTS

The authors would like to thank Laura Carroll for providing the creep-fatigue experimental data collected under the Next Generation Nuclear Plant Program and for her valuable comments. This work was supported under the U.S. Department of Energy Office of Nuclear Energy sponsored Light Water Reactor Sustainability program.

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