

# Properties of Alloy 617 for Heat Exchanger Design

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**Abstract** – Alloy 617 is among the primary candidates for very high temperature reactor heat exchangers anticipated for use up to 950°C. Elevated temperature properties of this alloy and the mechanisms responsible for the observed tensile, creep and creep-fatigue behavior have been characterized over a wide range of test temperatures up to 1000°C. Properties from the current experimental program have been combined with archival information from previous VHTR research to provide large data sets for many heats of material, product forms, and weldments. The combined data have been analyzed to determine conservative values of yield and tensile strength, strain rate sensitivity, creep-rupture behavior, fatigue and creep-fatigue properties that can be used for engineering design of reactor components. Phenomenological models have been developed to bound the regions over which the engineering properties are well known or can be confidently extrapolated for use in design.

### I. INTRODUCTION

One objective of the U.S. program to develop a Very High Temperature Reactor (VHTR) is to support design of a nuclear system with helium as the primary coolant to transport thermal energy for the cogeneration of hydrogen, process heat and electricity. The conceptual design requires an outlet temperature of greater than 850°C to provide for the efficient generation of hydrogen, with a desired maximum outlet temperature of 950°C. A critical component in the VHTR system for extracting thermal energy at these temperatures is the Intermediate Heat Exchanger (IHX), which will be required to operate at reactor outlet temperatures of up to 950°C. The combination of very high temperature operation and long duration of service dictates the need for structural materials with good thermal stability as well as high temperature creep and oxidation resistance. Based on these material requirements, the nickel base alloy UNS N06617, Alloy 617, is the leading IHX candidate alloy [1].

Licensing such a system requires use of the design rules in the ASME Boiler and Pressure Vessel

Code. The elevated temperature design analysis methodologies in the applicable part of the ASME Code, Section III, Subsection NH are predicated on the concept of protection against applicable structural failure modes and necessary for the design of a VHTR-type reactor in the temperature regimes where inelastic deformation occurs. A draft Code Case to incorporate Alloy 617 in the nuclear section of the ASME Code was developed in the 1980s [2]. Although action was suspended before the Draft Alloy 617 Code Case was accepted by ASME, it provides a strong information base for achieving codification of Alloy 617. Code qualification will have to account for unique high temperature behavior of that includes a lack of clear distinction between time-independent and time-dependent behavior, a high dependence of flow stress on strain rate, and time, temperature, and strain-dependent softening.

Specific weaknesses in understanding the elevated temperature properties of this material were identified in comments received on the Draft Alloy 617 Code Case and through more recent discussion with ASME. Greater understanding of the

creep-fatigue behavior of Alloy 617 and weldments was ranked as the highest priority, but additional data needed for high temperature design and constitutive model development including elevated temperature tensile, creep, and strain rate sensitivity as well as physical properties were identified [1].

Properties from the current experimental program have been combined with archival information from previous VHTR research to provide large data sets for many heats of material, product forms, and weldments. The combined data have been analyzed to determine conservative values of yield and tensile strength, strain rate sensitivity, creep-rupture behavior, fatigue and creep-fatigue properties that can be used for engineering design of reactor components.

## II. RESULTS

### II. A. Fatigue and Creep-Fatigue

Creep-fatigue deformation is expected to be a significant contributor to the factors that limit the useful life of the IHX in the VHTR nuclear system [1]. This deformation mode occurs as a result of power transients during operation and startup/shutdown cycles, each of which produces cyclic loading, while extended times at high temperature during steady power operation induce creep deformation. Extrapolation of creep-fatigue data, particularly at the extremes of the creep regime, using a set of design rules that is not overly conservative is a challenge. To approximate the expected deformation mode in a laboratory setting, creep-fatigue testing introduces a hold time in a strain-controlled fatigue cycle. Previous work on Alloy 617 has suggested that it is a tensile dwell sensitive alloy [3], and therefore that type of loading was the focus of this work.

In the U.S. nuclear design code creep-fatigue life is evaluated by a linear summation of fractions of cyclic damage and creep damage. The cyclic- and creep-damage terms are evaluated in an uncoupled manner, and the interaction of creep and fatigue is accounted for empirically by summing the two types of damage.

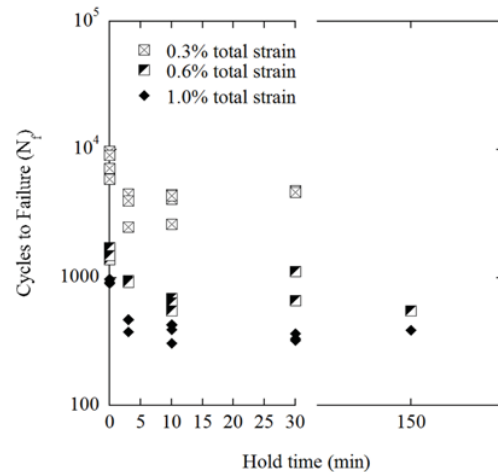
The creep damage term is evaluated as a ratio of the actual time the material is subjected to creep deformation during a creep-fatigue test versus the time to rupture determined from creep tests at a given temperature. The ratio is generally referred to as a time-fraction. As a result of the need to evaluate the creep damage, or time fraction, for the creep-fatigue analysis, extensive studies of the rupture life of modern heats of Alloy 617 have been carried out. These data have been combined with historical studies of the rupture behavior of the alloy and the resulting data set of approximately 500 tests are

combined into a Larson-Miller plot that describes rupture behavior over a wide range of stresses for temperatures from approximately 600 to 1000°C. These data are shown in section II. C.

The fatigue damage fraction for a creep-fatigue test is defined in terms of the ratio of the cycles to failure,  $n$ , under creep-fatigue conditions to the cycles to failure,  $N_f$ , under continuous cycling conditions for the same product form and heat, and at the same total strain range and temperature, as the creep-fatigue test. Extensive characterization of the fatigue and creep-fatigue behavior of Alloy 617 has been carried out at multiple strain ranges at temperatures of 850 and 950°C to support this creep-fatigue analysis. Hold times of as long as 150 minutes have been investigated.

Addition of a tensile hold time in creep-fatigue significantly degrades the number of cycles to failure relative to continuous cycle fatigue, as shown in Figure 1. At the higher temperature (950°C) this degradation in the number of cycles to failure saturates at relatively short hold times and continued degradation with increasing hold times is not observed. This is not the case at the temperature of 850°C. Furthermore, at the lower strain range at 950°C the cycles to failure in creep-fatigue is a function of the inelastic strain range at midlife [4, 5]. This Coffin-Manson type relationship does not hold at higher strain ranges at 950°C or for any strain range examined at the lower temperature of 850°C.

For heat exchanger design there will be a portion of the system where the alloy temperature is below the creep regime and elastic design rules in the ASME Code apply, i.e., Section III Subsection NB. A fatigue design curve has been determined for the maximum temperature, defined as 427°C, where creep behavior is not anticipated. A limited set of experiments was carried out to demonstrate that the fatigue behavior of Alloy 617 was conservatively described by nickel alloys already in the Code; the comparison is shown in Figure 2.



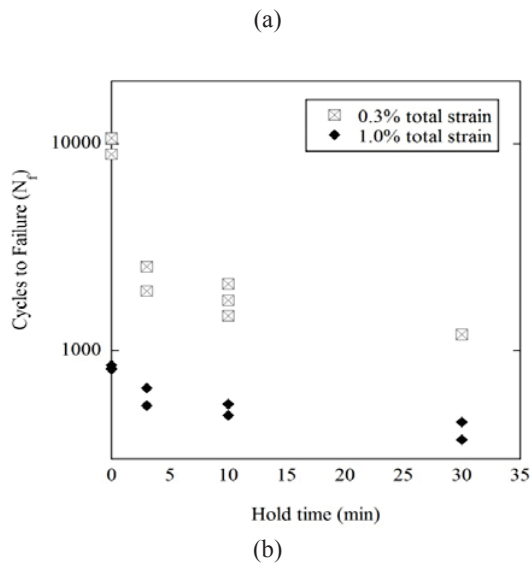


Fig. 1. Fatigue and creep-fatigue number of cycles to failure as a function of hold time for Alloy 617 at 950°C (a) and 850°C (b).

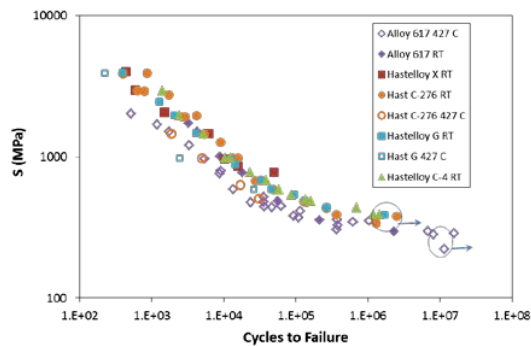


Fig. 2. Fatigue data for Alloy 617 for elastic design for temperatures up to 427°C. Data for Alloy 617 are shown along with data for several nickel alloys already allowed for nuclear design.

## II. B. Creep-Fatigue of Weldments

Despite the similar compositions of a weldment and base material, significantly different microstructures and mechanical properties are inevitable. In-service plant experience with Alloy 617 welds suggest that cracking has been observed at high temperature in weldments or in the adjacent base metal [6]. Preventing this type of failure is particularly challenging at high temperatures due to the variations in the inelastic response of the constituent parts of the weldment (i.e., weld metal, heat-affected zone, and base metal) and the changing mechanical properties of the weld due to an evolving microstructure during aging [6].

The creep-fatigue procedure in Subsection NH is established based on creep-fatigue data for base metal. It does not have a separate creep-fatigue procedure for welds. Instead, a number of conservative requirements are relied upon including: (1) limiting the inelastic accumulated strains to one-half the allowable strain limits for the base metal, (2) limiting the allowable fatigue at weldments to one-half the design cycles allowed for the base metal, and (3) potentially reducing the allowable creep-rupture strength at weldments to a fraction of the base metal value through the weld strength reduction factor (WSRF). The WSRF is a factor that reduces the creep-rupture strength of the weldment compared to that of the base metal when determining the time-to-rupture.

Gas tungsten arc welds with Alloy 617 filler metal were used to develop the weldment creep-fatigue data to assess the adequacy of this treatment of welds using the Subsection NH procedure under creep-fatigue conditions. Fatigue and creep-fatigue data for these weldments has been generated at 950°C and a 1.0% total strain range for hold times as long as 600 minutes.

The creep-fatigue behavior of welds is dramatically degraded relative to base metal and does not saturate within the range of hold times investigated, as shown in Figure 3. Cyclic testing that encompasses both the weldment and the surrounding base metal as opposed to only the weld metal is underway.

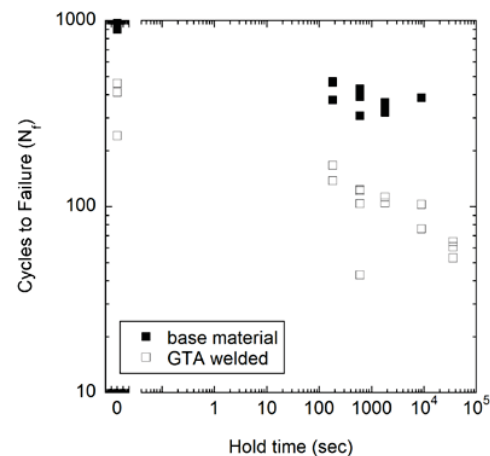


Fig. 3. Fatigue and creep-fatigue number of cycles to failure as a function of hold time for Alloy 617 GTA weldments at 950°C.

## II. C. Creep

For nickel based alloys such as Alloy 617, the secondary creep regime hardly exists at elevated temperatures and the onset of tertiary creep occurs very early in life at low creep strains. The gradually

increasing creep curve or absence of a secondary creep regime of Alloy 617 indicates the occurrence of a different deformation mechanism than materials that exhibit classical creep curves. Microstructural analysis of specimens from interrupted Alloy 617 creep tests performed at various temperatures and stresses and terminated at fixed total creep strains indicate that significant porosity, characteristic of the classical tertiary creep regime, is not present until 10% creep strain [7]. Instead a dislocation substructure forms prior to grain boundary cavitation or cracking and this substructure is believed to contribute to creep softening [5]. Thus the onset of tertiary creep behavior is not governed by porosity formation. These conclusions provide evidence supporting reconsideration of the ASME Code rules for determining the time dependent allowable stress for this class of high temperature alloys.

The specific creep mechanisms of Alloy 617 at the minimum or steady state creep rate were studied in the temperature range of 750 to 1000°C. At temperatures from 800 to 1000°C, typical power-law creep behavior with a stress exponent value of approximately 5 is observed. The minimum creep rates at 750°C, however, indicate threshold stress behavior due to the formation of ordered, coherent  $\gamma'$  precipitates present at a low volume fraction at this temperature [8]. It is evident from the Zener-Hollaman plot shown in Figure 4 that the normalized creep rate at 750°C deviates from the behavior of the alloy tested at higher temperatures. The threshold stress is determined experimentally to be in the range of 70 MPa at 750°C and is verified to be near zero at 900°C directly correlating to the formation and dissolution of  $\gamma'$  precipitates, respectively. As shown in Figure 5, using a threshold stress of this magnitude to correct the applied stress at 750°C results in the normalized creep rate at all temperatures falling on a single line. TEM analysis of specimens crept at 750°C to various strains, and modeling of stresses necessary for  $\gamma'$  precipitate dislocation bypass, suggest that the climb of dislocations around the  $\gamma'$  precipitates is the controlling factor for continued deformation at the end of primary creep and into the tertiary creep regime [8].

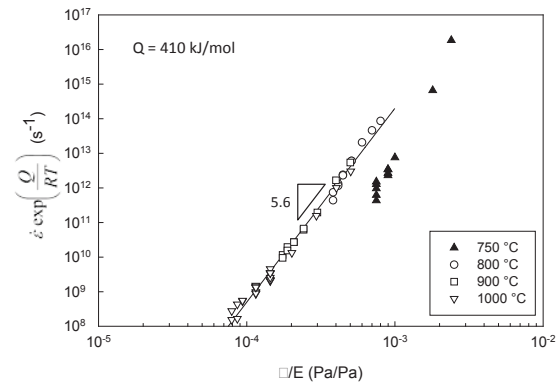


Fig. 4. Zener-Hollaman plot of minimum creep rates from 750 to 1000°C. The 750°C data are offset to the right of the data at the other temperatures indicating threshold stress behavior [8].

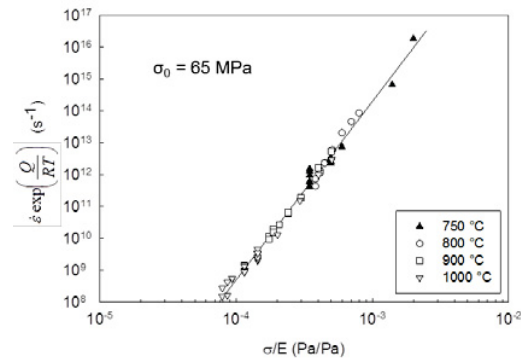


Fig. 5. Zener-Hollaman plot of minimum creep rates from 750 to 1000°C with the applied stress at 750°C data corrected using a threshold stress of 70 MPa [8].

In addition to minimum creep rate, the time to rupture is an important characteristic of high temperature alloys. Rupture lives for Alloy 617 are shown in the form of a Larson-Miller plot (with the constant taken to be 20) in Figure 6. Data from the current program are shown with historical data where the heat chemistry is known. An additional approximately 200 tests have been reported in the literature where the alloy chemistry is not specifically reported and can be used as confirmatory values, however, they are not shown in this figure.



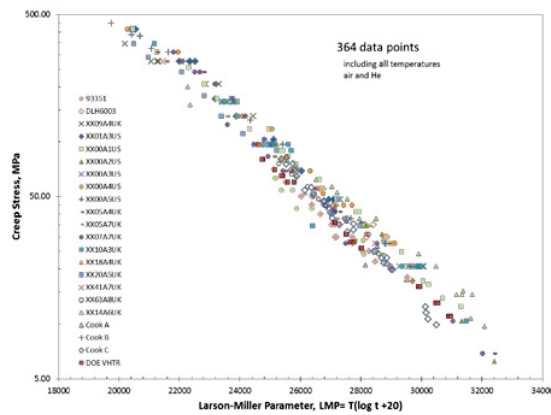


Fig. 6. Larson-Miller plot of Alloy 617 rupture data.

#### II. D. Strain Rate Sensitivity

Stress-strain curves change substantially as a function of test conditions in materials where the flow stress is a function of the applied strain rate at elevated temperature. Determination of the magnitude of this effect is required for constitutive models and is captured by the strain rate sensitivity parameter “m”. Strain rate sensitivity of Alloy 617 has been determined as a function of temperature over that range of temperatures relevant for these applications 650 to 950°C. The flow stress as a function of the strain rate for strain rate jump tests is shown in Figure 7. Above 800°C Alloy 617 is highly strain rate sensitive with a stress exponent similar to that observed for creep by a power law mechanism for the entire range of strain rates sampled ( $10^{-6}$  to  $10^{-2}$ /s). The flow stress of Alloy 617 becomes essentially insensitive to strain rate at 700 °C and below.

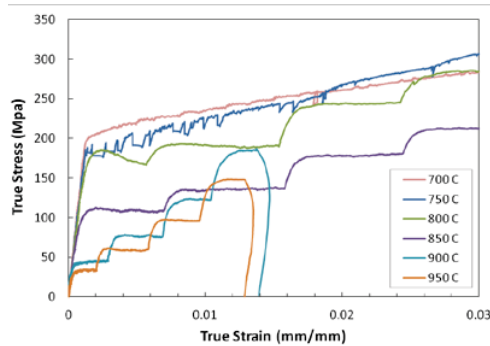


Fig. 7. Strain rate jump behavior of Alloy 617 over the temperature range 700 to 950°C.

#### II. E. Tensile Behavior

Yield strength and tensile strength at temperature are used to set the time-independent allowable stress for structural materials. As part of the Draft ASME Code case effort, a database was

compiled of yield and tensile strength data from tests performed in air by Huntington Alloys, Inc. determined when this alloy was under development. Section II, Part D, Appendix 5, recommends the submittal of tensile strength, yield strength, reduction of area, and elongation at 50°C intervals, from room temperature to 50°C above the maximum intended use temperature for a minimum of three industrial heats of appropriate product forms and sizes. The yield and tensile strength data used for the Draft Code case has been augmented with additional data from several modern heats generated by Idaho National Laboratory and Oak Ridge National Laboratory in the U.S. and CEA in France.

These data sets have been combined with the original Huntington Alloys to create a more complete data set for analysis, with 198 data points representing 14 heats and five product forms of Alloy 617. It was found that the yield strength data from the newer Alloy 617 heats are consistent with those from the older Huntington heats. However, the tensile strength data from the newer Alloy 617 heats are slightly lower than those from the Huntington heats. Curves showing a conservative minimum yield strength and average tensile strength, determined using the standard ASME method, are shown in Figure 8 for the combined data sets.

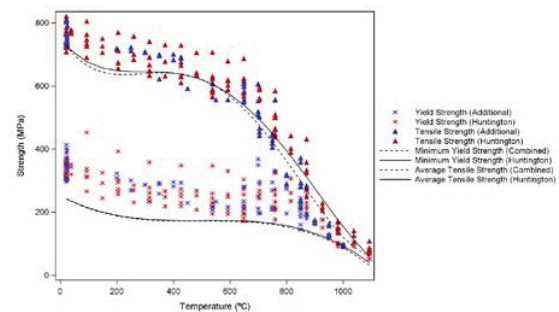


Fig. 8. Lower bound yield and average tensile stress for Alloy 617 determined using the ASME Code method.

#### II. F. Physical Properties

Physical properties are also necessary to support the Alloy 617 Code Case because, although Alloy 617 has been commercially available for many years and is included in the ASME Code for non-nuclear pressure vessel applications, its thermal properties were not previously well characterized. Thermal and physical properties of Alloy 617 that were determined by International Nickel Company (INCO), the successor to Huntington Alloys, during development of INCONEL® 617 are contained in data sheets supplied by the vendor (now called Special Metals Corporation). The reported values for thermal conductivity and specific heat were derived

by calculation from measurement of electrical resistivity as a function of temperature. The data appear to contain a significant amount of uncertainty from approximations and interpolations used in the calculations and conversion to SI units. A series of experiments were carried out on modern heats of Alloy 617 to determine the thermal diffusivity, thermal expansion behavior and specific heat capacity of four different heats of Alloy 617 at temperatures ranging from 25°C to 1000°C. These measured values allow calculation of the thermal conductivity, shown in Figure 9.

Elastic properties for the alloy have also been measured and extended to temperatures above 950°C. These measurements were made using standard flexural methods and by independent measurements of the longitudinal and shear wave velocities using laser ultrasound methods. The Young's modulus measured using these methods are shown in Figure 10. Data from the current ASME Code and vendor datasheets are also shown in the figure for comparison.

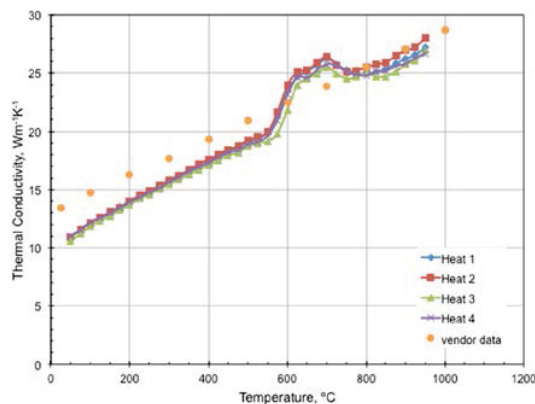


Fig. 9. Thermal conductivity of four different heats of Alloy 617 compared to vendor data.

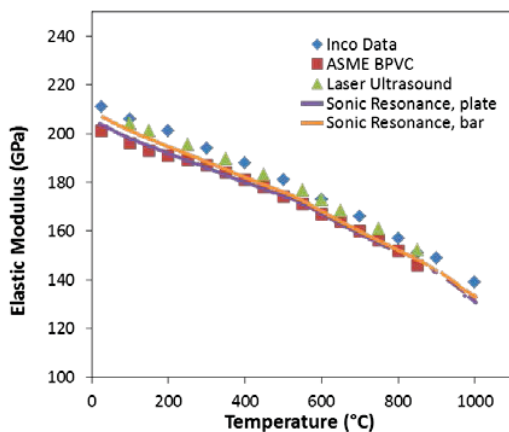


Fig. 10. Young's modulus measured using laser ultrasound and flexural methods compared to data in vendor datasheets and the ASME Code.

### III. DISCUSSION AND CONCLUSIONS

Elevated temperature mechanical properties have been determined for a contemporary heat of Alloy 617, including tensile, creep, creep-fatigue and fatigue behavior. These measurements have been combined with a large amount of information that was determined during previous VHTR development programs. The combined data sets provide the basis for engineering design for high temperature heat exchangers.

Creep-rupture behavior is well described using the Larson-Miller formulation over a wide range of time, temperature and stress conditions. Over the range of conditions examined there is no evidence of a change in deformation mechanism (e.g., to diffusional processes) that would preclude extrapolation to times longer than those examined experimentally.

It has been shown that the influence of tensile hold-time saturates in creep-fatigue testing for relatively short times at 950°C; saturation has not yet been observed at 850°C.

Alloy 617 exhibits significant strain rate sensitivity above 700°C even for strain rates typical of tensile loading. Although yield and tensile strength values are specified for temperatures up to 1000°C, it must be recognized that these values are valid only for the strain rate specified in the ASTM E 6 elevated temperature tensile testing standard.

The fatigue design curve for nickel alloys that is currently in the Code for design in the temperature range appropriate for elastic design has been shown to adequately describe behavior of Alloy 617.

The physical properties of this alloy have also been reexamined in this program. Newly determined results are generally consistent with previously published values within the  $\pm 5\%$  confidence limits specified in the Code. Additional data will allow extension of the design values to above 950°C.

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