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Predicting Creep in an Alloy 617 Pressure Vessel Using Uniaxial Bar Test Data

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Abstract

Alloy 617 is being investigated as a candidate for application in next generation nuclear plants (NGNPs), including the very high temperature reactor (VHTR). Creep deformation concerns the lifetime and failure of heat exchangers used at the very high operating temperatures and pressures of such plants. In order to meet the American Society of Mechanical Engineers' Boiler and Pressure Vessel code (ASME B&PV), and be certified for use in NGNPs, a thorough understanding of creep must be demonstrated. Current methods of testing creep have limitations and there remains uncertainty and controversy as to the applicability of these tests to more complex designs[1,2]. The aim of this research is to relate data from uniaxial laboratory creep tests to multiaxially loaded service components.

Disciplines

Materials Science and Engineering

Authors

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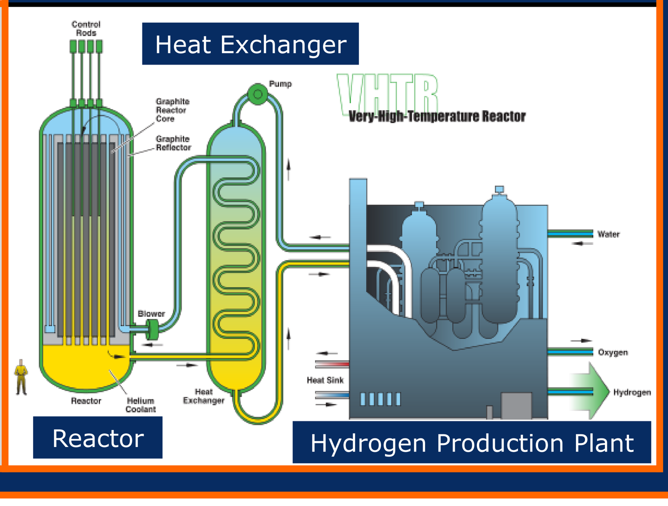
1. Introduction

Alloy 617 is being investigated as a candidate for application in next generation nuclear plants (NGNPs), including the very high temperature reactor (VHTR). Creep deformation concerns the lifetime and failure of heat exchangers used at the very high operating temperatures and pressures of such plants. In order to meet the American Society of Mechanical Engineers' Boiler and Pressure Vessel code (ASME B&PV), and be certified for use in NGNPs, a thorough understanding of creep must be demonstrated. Current methods of testing creep have limitations and there remains uncertainty and controversy as to the applicability of these tests to more complex designs[1,2]. **The aim of this research is to relate data from uniaxial laboratory creep tests to multiaxially loaded service components.**

Reactor Design

Very High Temperature Reactor



2. Background

The very high temperature reactor (VHTR) design[1,2]:

- Exceeds the energy production of current reactor designs while also producing hydrogen
- Requires operating temperatures between 750 to 1000°C (~1400 to 1800°F)
- Uses helium cooling gas at pressures up to 8MPa (~1160psi)

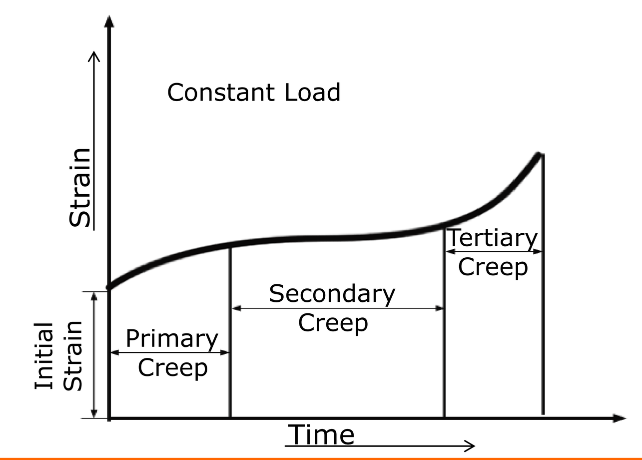
Creep, a high temperature process resulting in deformation at low stresses, severely limits material selection. Alloy 617, a nickel-based alloy, is the leading candidate for use in heat exchangers.

Composition of Alloy 617

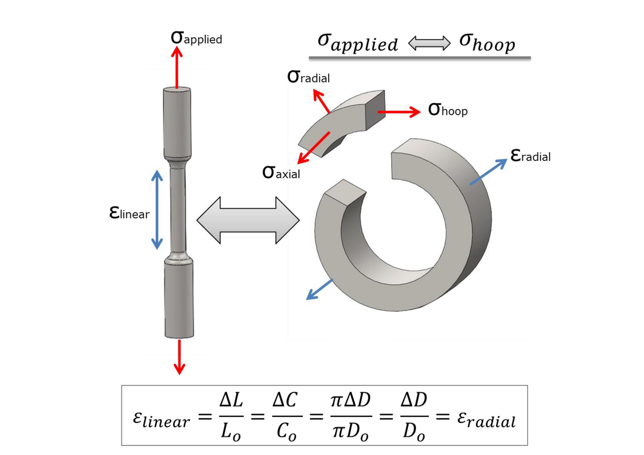
Element	Ni	Cr	Co	Mo	Fe	Al	Ti	Mn	Si	C,Cu,S,B
Weight %	54.1	22.2	11.6	8.6	1.6	1.1	0.4	0.1	0.1	≤0.05

Creep Behavior

Typical Creep Curve



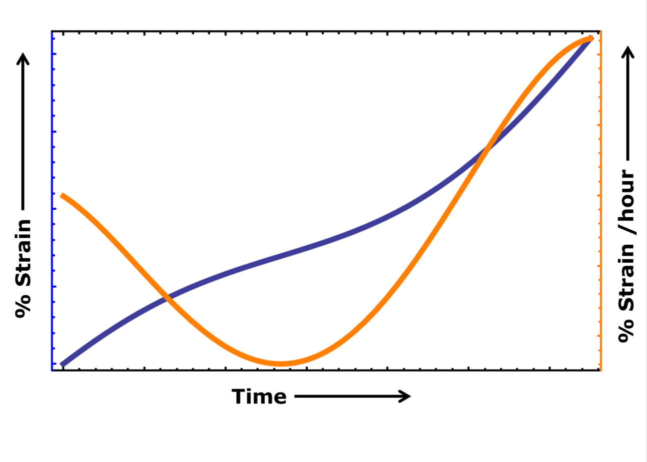
Bar Test Related to Tube Test



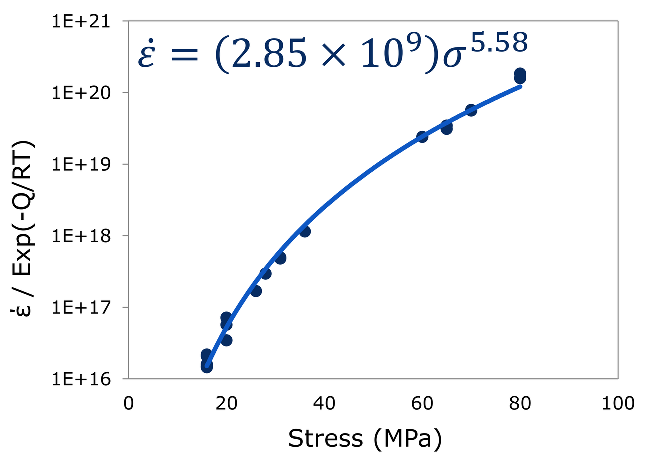
3. Approach

Creating a Constitutive Model

Creep Strain and Strain Rate



Parameters From Uniaxial Tests



The simple Norton-Bailey relationship, below, was used to model data from existing uniaxial creep tests ranging in temperature from 800 to 1000°C, and stresses of 16 to 80 MPa.

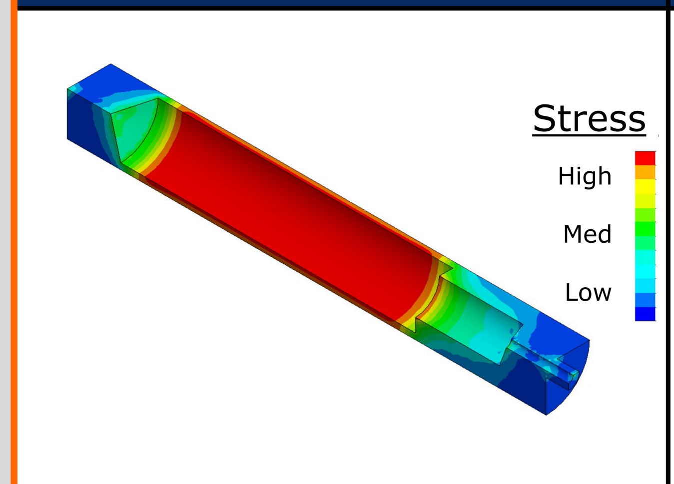
$$\dot{\varepsilon} = A\,\sigma^n \exp^{-Q/_{RT}}$$

Where A is a normalizing factor, σ is an applied stress, n is the stress exponent, Q is the activation energy for creep, R is the gas constant and T is absolute temperature.
The following assumptions have been made:

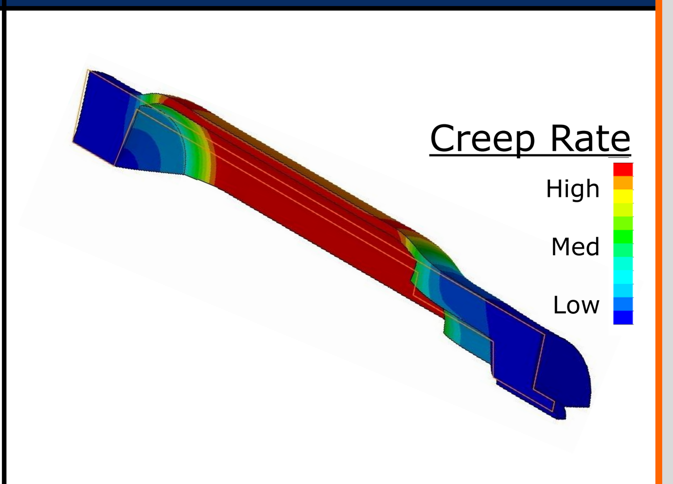
- Using the Norton-Bailey relationship gives an accurate prediction of small levels of strain
- The elongation of a bar test can be related to the diametric expansion in a pressure vessel

Finite Element Analysis and Simulations

Von Mises Stress State of ¼ Vessel



Simulated Creep Deformation



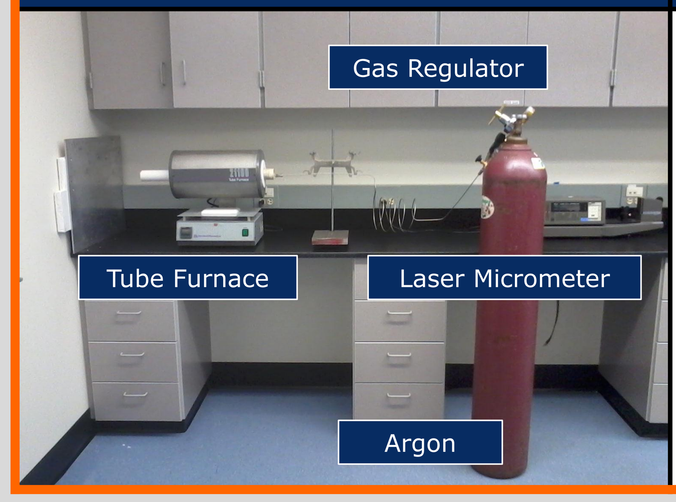
A replica of the experimental pressure vessel was modeled in SolidWorks. Finite element analysis (FEA):

- Verified the Von Mises stress state of the sample
- Utilized the material parameters extracted from the uniaxial tests
- Employed the Norton-Bailey creep relationship

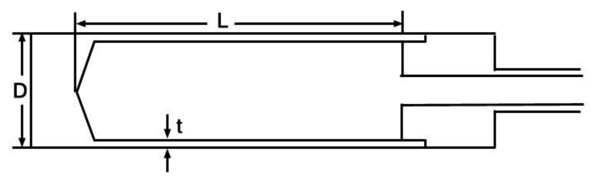
The constitutive model and FEA can both be used to predict creep strain in experimental samples.

Verification Tests Setup

Setup



PV design



Sample Geometries

Designation	Geometry A	Geometry B
Diameter (in/mm)	0.50 /12.70	0.75 /19.05
Length (in/mm)	2.0 /63.5	2.0 /63.5
Thickness (in/mm)	0.035 /0.89	0.039 /1.00

Experimental creep tests were performed on samples of tubular geometry to validate the predictions made by the constitutive and computer models. Samples were:

- Machined from the same batch of Alloy 617 used for bar tests
- Produced in two pieces and welded together
- Internally pressurized by an attached argon cylinder

4. Results

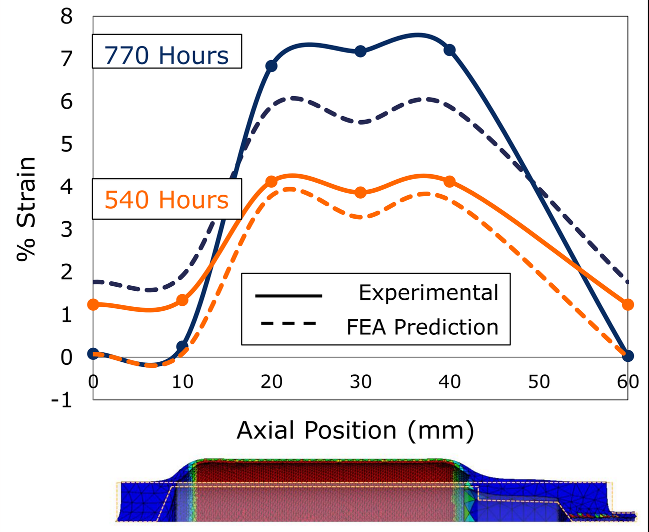
Limited to the linear region of creep, predicted strain from the two models accurately predict small levels of strain, with FEA giving a conservative prediction, and the constitutive model an underestimation.

Summary of Results

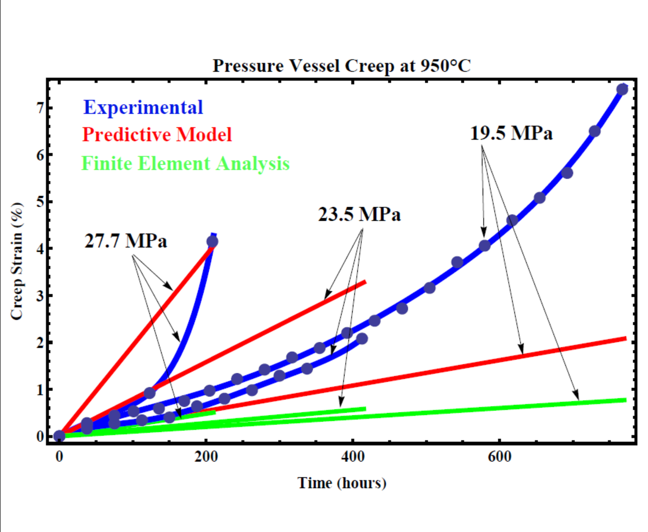
Parameter	Condition 1	Condition 2	Condition 3
Temp (°C)	950	950	950
Sample Geometry	A	B	B
Outer Hoop Stress (MPa)	19.5	23.5	27.7
Predicted Strain Rate (%/hr)	0.0027	0.0079	0.0193
FEA Strain Rate (%/hr)	0.0010	0.0014	0.0024
Experimental Strain Rate (%/hr)	0.0042	0.0021	0.0059

Plots of Experimental Creep Strain

FEA Prediction vs. Experimental



Comparative Results

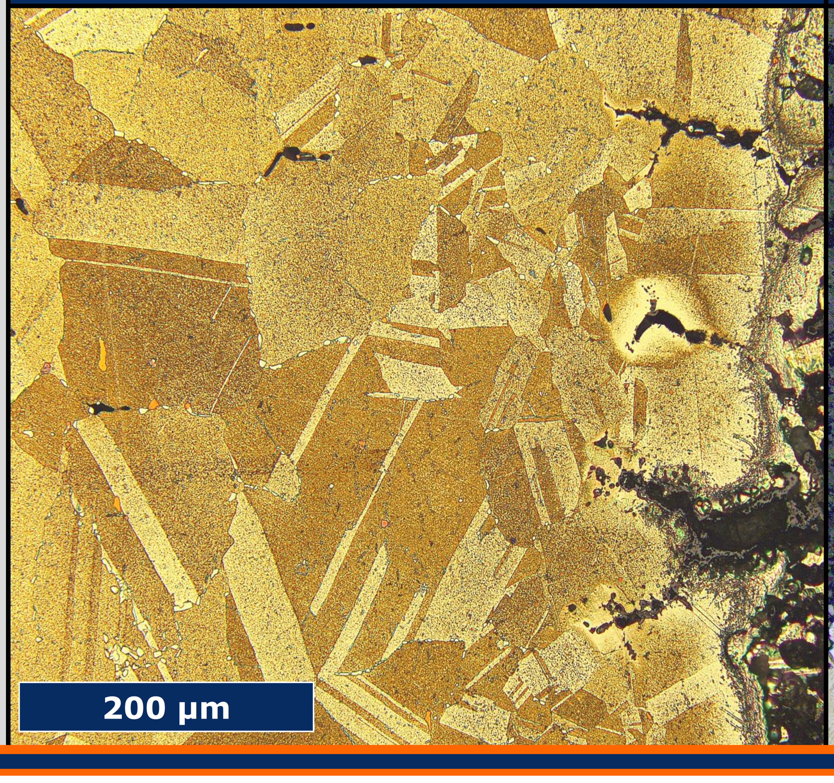


5. Characterization

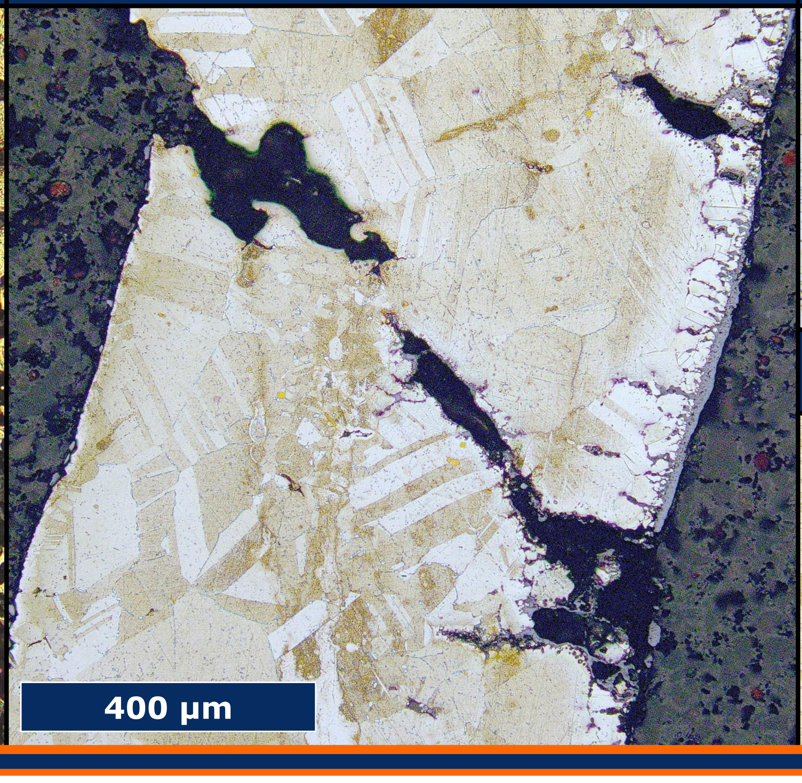
Characterization revealed creep mechanisms seen in bar tests are also observed in this test.

- Purely thermal aging shows shallow oxidation and no carbide coalescence
- Thermo-mechanical aging shows deeper oxidation, carbide coalescence and void formation
- Failure occurs by these voids

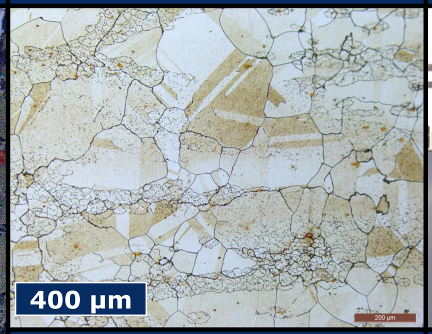
Pressure Vessel Wall at 7% Strain



Crack in Pressure Vessel Wall at 7.5% Strain

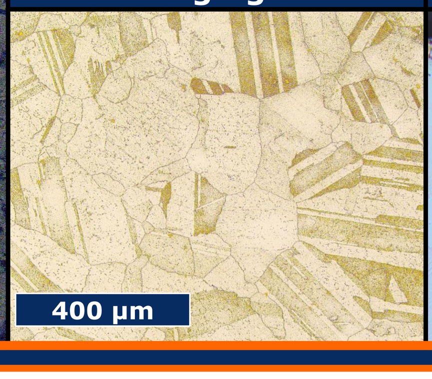


Alloy 617 As Received

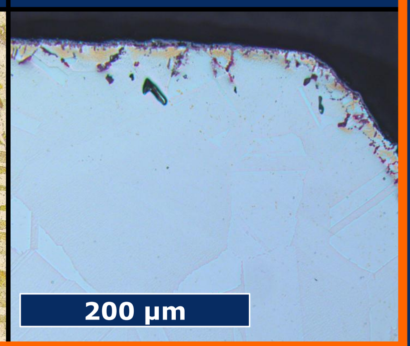


Test Sample Failure

Alloy 617 Thermal Aging



Oxidized Alloy 617



6. Conclusions

- A method to induce and monitor radial creep was developed using this method of internally pressurized tubes
- Microstructural characterization revealed a link in mechanisms between bar and tube tests, supporting the application of existing creep data to service components[3,4]
- The predictive model and FEA simulation constructed with parameters specific to Alloy 617 is believed valid for the temperatures 800 to 1000°C and can predict creep strain to small levels in a pressure vessel

VHTR Technology Development Office
R&D FOR NGNP AND BEYOND

Acknowledgements

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