MULTIAXIAL EXPERIMENTATION ON

CREEP-FATIGUE-RATCHETING BEHAVIOR OF INCONEL 617

A Thesis in

Engineering Mechanics

by

Mainak Sengupta

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The thesis of Mainak Sengupta was reviewed and approved* by the following:

Clifford J. Lissenden  
Professor of Engineering Science and Mechanics  
Thesis Adviser

Charles E. Bakis  
Professor of Engineering Science and Mechanics

Reginald F. Hamilton  
Assistant Professor of Engineering Science and Mechanics

Judith A. Todd  
Professor of Engineering Science and Mechanics  
Head of the Department of Engineering Science and Mechanics

*Signatures are on file in the Graduate School.
ABSTRACT

Materials play an important role in human society and find uses in diverse areas like load–bearing structures, semiconductors and biological applications. High-temperature nuclear power reactors are one of these applications that require novel materials for extreme environments. High-temperature nuclear reactors are predicted to provide higher efficiency and cleaner power for society. Inconel 617 is one of the candidate materials for constructing components of high-temperature reactors. Considerable time and effort must be spent in order to understand the viscoplastic behavior of the material before it can be put into use. Material behavior depends on temperature, loading rate, loading paths and other factors. This thesis presents multiaxial experimental results for Inconel 617 specimens using an axial-torsion test machine. Multiaxial experiments were conducted on Inconel 617 tubular specimens for two non-proportional loading paths, MR1 and MR2, at two different temperatures, 950°C and 850°C, and at two different strain rates, 0.1%/s and 0.04%/s. The MR1 experiment was controlled in steady axial stress and cyclic shear strain. The MR2 experiment was a bow-tie path controlled in cyclic axial stress with holds at maximum and minimum stress and cyclic shear strain. These tests simulated creep-fatigue-ratcheting behavior in Inconel 617. These results will aid in the development of unified constitutive models, so that nuclear components can be designed for longer operational lives. The higher temperature tests led to more plastic strain accumulation and lower stress levels in the specimen. The higher loading rates led to higher stress levels and lower plastic strain for the MR1 experiments. The behavior of Inconel 617 for the MR1 and MR2 loading paths is significantly different.
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Chapter 1

Introduction

Mankind’s progress over the course of history has depended on discoveries and inventions. These have ranged from simple discoveries like lighting a fire or the introduction of the wheel to more complex ones like the invention of automobiles or fabrication of smaller semiconductor chips that make complex computing possible. All these applications involve materials and are used in a range of different ways. Flintstones help us light a fire, metal and rubber can be used to construct wheels, alloys and composites are routinely used for automobile chassis and integrated-circuit chips made from silicon have revolutionized the computing industry. Man’s quest for lighter, stronger and better materials is never-ending as improved materials help us build smarter, durable and cost effective products.

One of the major uses of materials is in the structural components. Most structural components use metal or metal alloys of various types. Although metals are capable of providing excellent strength, alloys help us combine and improve different properties. One of the alloy systems that has been studied and is of great interest to scientists is Nickel-based alloy (Ni-based). Ni-based alloys provide higher strength than most conventional steel or other ferrous based alloys. Ni-based alloys have excellent stability, very high corrosion resistance, resist creep and retain their mechanical properties over a wide range of temperature. These properties are helpful for high temperature applications like gas-turbine blades and aerospace structures. They are also used in the chemical industry particularly in corrosive environments like the components of heat exchangers and furnaces, in waste remediation units and flares,
chemical processing and petrochemical processing. Typically many Ni-based alloys find use in applications that are exposed to extreme environments where a combination of high temperature, high stress, carburizing or corrosive environment is present.

The composition of Ni-based alloys typically includes copper, iron, chromium, molybdenum, cobalt, manganese and aluminum. Some common Ni-based alloys are Monel, Hastelloy A, Inconel X and Invar. The main highlight of this thesis is to investigate the mechanical behavior of Ni-alloy Inconel 617. Inconel 617 is a solid-solution strengthened alloy that is composed largely of nickel, cobalt, chromium and molybdenum as shown in Table 1.1 [1]. It is capable of retaining its strength and hardness at very high temperatures and is also resistant to creep and corrosive environments. Its strength at high temperature is imparted by the solid-solution of cobalt and molybdenum. The melting temperature range for Inconel 617 is 1332 – 1377°C.

Table 1.1: Limiting chemical composition of Inconel 617 in % [1]

<table>
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<tr>
<th></th>
<th>Ni</th>
<th>Cr</th>
<th>Co</th>
<th>Mo</th>
<th>Al</th>
<th>C</th>
<th>Fe</th>
<th>Si</th>
<th>Ti</th>
<th>Mn</th>
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<tr>
<td></td>
<td>44.5 (min)</td>
<td>20.0-24.0</td>
<td>10.0-15.0</td>
<td>8.0-10.0</td>
<td>0.8-1.5</td>
<td>0.05-0.15</td>
<td>3.0 (Max)</td>
<td>1.0 (Max)</td>
<td>0.6 (Max)</td>
<td>1.0 (Max)</td>
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These properties interest material scientists who envisage it to be the material of choice for many high temperature applications in the power and aerospace industry. One of the major end uses for Inconel 617 will be in the nuclear industry especially in Next Generation Nuclear Power plants (NGNP), shown in Figure 1.1 [2]. Over the last few years scientists increasingly find nuclear energy as an attractive option among the many different sources of energy available [3]. Nuclear fuel can deliver large amounts of electricity and is reliable, which is an issue for wind or solar power. Another attractive feature of nuclear power plants is that unlike coal or gas-based plants, they do not emit carbon dioxide and other greenhouse gases.
Due to these advantages, the U.S.—Department of Energy acting on the recommendations of senior scientists has taken key initiatives in developing the once-through fuel cycle nuclear plants and has started the Next Generation Nuclear Program (NGNP) [4]. NGNP aims to build better and improved Generation 4 nuclear plants [5]. NGNP is currently in the process of developing a Very-High-Temperature Reactor (VHTR) technology. This is a graphite-moderated, helium-cooled reactor with a once-through uranium fuel cycle. The outlet temperature of the VHTR will range from 850°C to 950°C. We know from thermodynamic considerations and analysis of Carnot cycle that the efficiency of a process improves as the difference between the outlet and inlet temperature is raised. The VHTR is expected to operate at an efficiency of 45% compared to 33% for Light-Water-Reactor based plants, and can potentially solve many of our energy needs. The high outlet temperature will also find
applications in hydrogen production for the process plant industry. The VHTR will be able to provide low risk and cost effective nuclear power for the consumers. Electricity will be produced through an indirect cycle with an intermediate heat exchanger, which will transfer the heat for hydrogen generation or to a gas turbine.

However, operating power plants at this temperature will be exceedingly challenging. Most of the components of a conventional plant are built from materials that cannot function at such elevated temperatures. One of the most critical components is the intermediate heat exchanger tubing and reactor components. These components will be subjected to uni-axial and multi-axial loads at elevated temperatures. Alloy 617 has been selected as a candidate material for building the components of the NGNP, particularly for the tubing in the intermediate heat exchanger (IHX) [6]. However, not much data is available at an elevated temperature range for Inconel 617 and no unified model exists for simulating its viscoplastic behavior. Therefore it is imperative to comprehensively understand the material behavior of Inconel 617 at high temperature before using it in high temperature reactors.

The remainder of this chapter describes the thesis objectives and provides a literature review. The objectives explain how this research on Inconel 617 will help scientists gain a better understanding of its behavior and expedite the implementation of next generation nuclear technology. In the second part, a literature review of the micro-structural properties, mechanical behavior of Inconel 617 and material modeling are presented.
1.1 Objectives

The intermediate heat exchanger (IHX) component of the NGNP will be subjected to thermo-mechanical low-cycle fatigue (LCF) loading with hold periods [7]. LCF loading will occur due to reactor start-ups and shut-downs and the hold period is introduced during the normal plant operation in which the components will operate at elevated temperatures ranging between 850°C - 950°C and 8 MPa pressure. Thus, the NGNP will be subjected to severe and challenging conditions. The Independent Technical Review Group (ITRG) has specifically identified IHX as a high risk NGNP component [8]. This research undertakes multi-axial loading tests on Inconel 617 at elevated temperatures of 850°C and 950°C, thereby creating similar conditions that the IHX components will experience [9]. One of the primary objectives is to simulate creep-fatigue and creep-ratcheting in Inconel 617. This viscoplastic behavior of Inconel 617 will provide data for updating the ASME-NH code. Currently the ASME-NH code for Inconel 617 is provided only up to 650°C. Based on these multi-axial data and other uni-axial experiments, a Unified Constitutive Model (UCM) will be developed and validated by research partners at North Carolina State University. The UCM will help engineers adopt the design-by-analysis method while designing or modeling critical Generation IV nuclear components like heat exchangers and reactors. Another important objective is to scrutinize the material response of Alloy 617 to creep-fatigue-ratcheting interaction and failures based on these phenomena. Other material behaviors that are expected to be observed are loading rate and strain range dependence and effect of non-proportional loading on the material response.
1.2 Literature review

1.2.1 Inconel 617 Microstructure

Inconel 617 is a solid-solution strengthened face-centered-cubic (FCC) alloy which is typically composed of 45% nickel, 20-25% chromium, 10-15% cobalt, 8-10% molybdenum described by its manufacturer’s document [1]. The nickel and chromium provides resistance to reducing and oxidizing environments and the strengthening effect is provided by the cobalt and molybdenum. The nickel also provides the alloy with high ductility under high stress. The modulus of elasticity and 0.2% yield strength of the materials at room temperature are approximately 211 GPa (30600 ksi) and 350 MPa (50 ksi) respectively. However at higher temperatures, strength is much lower. The yield strength reported for Inconel 617 at 1093°C (2000°F) is 70 MPa (10 ksi). Since this material is a primary candidate for low-cycle fatigue (LCF) applications, engineers have tried to balance both LCF strength and creep resistance at high temperatures. An ASTM grain size of 4 and 5 is found to significantly improve the creep resistance compared to lower grain sizes. This is expected as a creep resistance is directly proportional to grain size. The material also has excellent creep-rupture strength.
Kihara et al. investigated the morphological changes of carbides at 1000°C [10]. Creep tests were carried out at 1000°C under 24.5 MPa stress (results shown in Figure 1.2). The authors report that carbide free specimens showed a higher creep rate and shorter creep rupture life time. At high temperature, $M_{23}C_6$, $M_6C$ and $\gamma'(Ni_3Al)$ are found to precipitate along grain boundaries as well as in the grains within the alloy, shown in Figure 1.3. Here, M could be a metal like molybdenum or chromium. This has been confirmed by scanning electron microscopy (SEM) and transmission electron microscopy (TEM) images. The grain size and carbide precipitation and stability all play an important role in determining the creep strength of Inconel 617.
This carbide precipitation leads to an anomalous increase in the yield strength of the alloy at 800°C and 900°C. Roy and Marthandam [11] have studied this anomalous property and attribute it to the formation of $Cr_23C_6$ and $Mo_{23}C_6$ precipitates. Scanning and Transmission Electron Microscopy (SEM and TEM) images show that samples tested at 900°C under tensile loading have precipitates, pinned dislocations and dislocation pile-ups at the grain boundaries as shown in Figure 1.4. The authors have also noted the formation of smaller sub-grains that increase the yield strength in conformance with the Hall-Petch effect. Energy-Diffraction spectroscopy (EDS) and X-ray diffraction (XRD) performed on the matrix and the precipitate confirmed that the concentration of chromium, molybdenum and carbon were higher and nickel concentration was much reduced. Void formation in Inconel 617 at high temperatures has been investigated by Lillo et al. [12]. Void formation is reported to have occurred after the material had undergone a large amount of creep at high temperature. The voids were also found to have formed on the grain boundaries.
Creep behavior of Inconel 617 has been studied by Cabibbo et al. [13]. Tests were performed at 700°C and 800°C as these were the hardening and softening temperatures for the alloy and optical microscopy (OM), SEM and TEM images (shown in Figure 1.5) were used to study the microstructural changes in the alloy. Exposure at 700°C and 800°C led to the intragranular precipitation of $\gamma'$ ($Ni_3(Al,Ti)$). A $\delta$-phase ($Ni_3Mo$) was also found to precipitate at 700°C. These phases were observed along with the carbide precipitation that had occurred at the grain boundaries. The improved creep resistance at 700°C was attributed to the size and distribution of $\gamma'$ precipitates in the alloy. The fraction of $\gamma'$ particles in the heat treated specimen was greater than that for the as received specimens. This greater volume fraction of the secondary phase particles was enough to improve the mechanical properties. Therefore research in the material microstructure suggests that the material is not only solid-solution strengthened but also carbide-strengthened.
10

Figure 1.5: SEM and TEM images show inter and intra-granular particles of precipitates and gamma prime particles [13].

1.2.2 Mechanical Behavior of Inconel Alloy 617

One of the primary concerns for NGNP plants is the intermediate heat exchanger that will experience thermo-mechanical low-cycle fatigue loading with long hold periods at peak temperatures within 850°C – 950°C and pressures up to 8 MPa during start up and shut down periods. Fatigue damage occurs during start-up and shut-down periods whereas creep damage can occur during dwell times. Therefore, it is important to understand the creep-fatigue and creep-ratcheting interactions in Inconel 617.

Creep is the accumulation of strain in the material when the stress is held constant [14]. Creep becomes more important for metal alloys at higher temperatures. Creep failures are excessive deformation failures or creep-rupture type failures. Creep occurs in materials due to
the thermally-activated migration of dislocations, grain boundary shearing and diffusion of vacancies. Generally, it is a combination of these along with high stresses that leads to creep damage.

**Ratcheting** is progressive deformation or accumulation of strain in a material over a number of cycles. Components that are subjected to a constant primary load and a varying secondary load show ratcheting behavior. Ratcheting failure involves very large deformation which renders the component non-functional in its intended service [15]. A ratcheting analysis based on a nuclear design code is part of component analysis for nuclear power plants. Ratcheting occurs due to inelastic material behavior. If the progressive deformation is finite then that limit is called plastic shakedown. Infinite ratcheting continues till component failure. Ratcheting can be of two types – material and structural. Material ratcheting is defined as ratcheting under uniform stress distribution whereas structural ratcheting as when the stress distribution is non-homogenous.

**Fatigue** on the other hand is the reduction in load-carrying capacity associated with cyclic loading. Such loadings are very common in almost all structural members. Airplanes, turbines and bridges are some of the most common kind of structures that are exposed to variable loading. Fatigue failures are typically driven by crack-nucleation and growth. Materials under fatigue load experience cyclic tensile and compressive loads that help micro-structural defects like cracks to propagate. Fatigue loading can be of two types - high-cycle and low-cycle fatigue based on the number of cycles to failure [16]. High-cycle fatigue is characterized by failures over 10000 cycles and low-cycle fatigue is defined as failures less than 10000 cycles.
Creep-fatigue interaction for Inconel 617 has been investigated by Totemeier et al. [17].

Series of tests were performed at 1000°C on a servo-hydraulic test machine at strain ranges of 0.3% and 1.0%. A trapezoidal test waveform with ramp rate of $1 \times 10^{-3}$/s was used to simulate fatigue load. Tensile hold periods at maximum strain from 18 to 1800 seconds were used to introduce creep. The tests were also conducted under different environmental conditions – in air and inert gas atmosphere. The inert environments were vacuum and argon gas chamber. The relaxation curves from the tests indicate that a gradual softening occurred for all the tests, shown in Figure 1.6. The cycles to failure plotted against the tensile hold time indicated that creep-fatigue life was reduced as hold time was increased and this effect was more prominent at the 0.3% strain range tests. Material was found to last longer in inert environment, although no quantification could be provided. The number of cycles to crack initiation was higher for samples tested at 0.3% strain and lower for 1.0% strain tests. This was consistent with commonly observed trends that for high-cycle fatigue cracks occur at the end of its life and for low-cycle fatigue, it is initiated early. Creep-fatigue life for specimens tested in air was also influenced by the oxidizing environment. External scales were observed on the specimens. Crack initiation at the oxidized grain boundaries led to failure. The authors also report that the environment seem to play an important role in deciding the creep-fatigue life of the alloy.
Similar creep-fatigue interactions on alloy 617 were studied by Rao et al. [18]. This study focused on creating similar environmental conditions that the material will experience in the IHX. Therefore tests were conducted in strain control and in impure helium environments. The effect of strain rate, hold conditions in tension and compression and hold time, were investigated. Strain controlled fatigue tests at 950°C and 0.6% strain range were carried out to analyze the low-cycle fatigue effects. Four different waveforms – continuous cycling, tensile hold, compressive hold and symmetrical hold, with a strain rate of $1 \times 10^{-3}$/s were used for the experiments. The findings were consistent with the studies of previous authors like Totemeier et al. Lower strain rate decreased the number of cycles to failure as there was a continuous increase in the inelastic strain component. Hold times were found to lower the fatigue life of the material. Hold times in tension were found to be worse than that for compression and hold periods in compression caused the material to fail by necking. Equal hold time was found to damage the specimen much less than either tensile or compressive hold. Tensile hold time led to stress relaxation, where it was observed that for a short hold time the stress values dropped.
to zero. Fractographic analysis (Figure 1.7 a - d) showed that 1 minute tensile hold led to transgranular cracks whereas compression hold periods led to dimple fracture.

![Fracture surface showing different crack propagation mechanisms](image)

Figure 1.7: Fracture surface shows different kinds of crack propagation mechanisms—(a) transgranular (b) mixed-mode (c) intergranular and (d) dimple fracture for different hold time and hold position. [18]

The alloy also showed the formation of carbides and precipitates at the grain boundaries as previous authors have reported. Oxidation and corrosion due to the formation of chromium oxide layer on the surface led to an increase in the fatigue crack propagation, shown in Figure 1.8.

![Surface oxide layer and secondary crack](image)

Figure 1.8: Surface oxide layer (left) and secondary crack. Grain boundary cavitation (right) seen in Inconel 617 specimen tested at 1000°C [18].
Inconel 617 is also reported to undergo serrated yielding or dynamic strain aging (DSA) at high temperature and low strain rates by Rahman et al. [19]. Dynamic strain aging occurs under strain control testing and is distinguished by negative strain rates or serrations in the stress-strain diagram as shown in Figure 1.9. The authors also report that carbide precipitation was observed, corroborating the findings of previous researchers.

![Figure 1.9: Serrated yielding for Inconel 617 and effect of strain rate on yielding [19].](image)

Since no results for studying ratcheting behavior is available in literature for Inconel 617, results for SUS304 are presented. Uniaxial and biaxial experiments to study ratcheting were conducted by Yoshida et al. [20] on SUS304 stainless steel at room temperature in stress control. Biaxial experiments were conducted with constant internal pressure and cyclic straining.
at different strain rates at room temperature. A large amount of ratcheting strain accumulated in the material under different loading conditions except under fully reversed loading or $R = \frac{\sigma_{\text{min}}}{\sigma_{\text{max}}} = -1$. Select examples are shown in Figure 1.10. The authors also report that strain accumulation is found to increase with peak tensile holds whereas strain accumulation during continuous cycling is not as large. Biaxial ratcheting is found to have strain rate dependence. Lower strain rate leads to higher ratcheting strain.

![Figure 1.10: Creep-ratcheting behavior of SUS304 with same rate but different $R=0.8$ and $R=0$ [20].](image-url)
1.2.3 Constitutive Modeling

Material behavior of Inconel 617 at high temperature is viscoplastic with dependence on strain-range, proportionality of loading, loading rate and many other factors. Since deformations occurring in the material will be permanent, plasticity theories are needed to accurately describe the material behavior. Classical plasticity theories define the non-reversible deformations in terms of a yield function, flow rule and hardening parameter. These theories are phenomenological and require complex testing for model development and validation. A yield function is used to define a definitive point in the stress space beyond which plastic deformation or yielding occurs. An example of a simple yield function, flow rule and hardening parameter is given below.

\[
f(\sigma_{ij}) = \sqrt{\frac{3}{2} (s - a) \cdot (s - a)} = k \tag{1.1}
\]

\[
d\varepsilon^p = \frac{1}{k} \left[ \frac{\partial f}{\partial \sigma} \cdot d\sigma \right] \frac{\partial f}{\partial \sigma} \tag{1.2}
\]

\[
da = g(\sigma, \varepsilon^p, a, d\sigma, d\varepsilon^p, etc) \tag{1.3}
\]

where, \(\sigma_{ij}\) is the stress tensor, \(s\) is the deviatoric rank 2 stress tensor, \(a\) is the current center of the yield surface and also a rank two tensor, and \(k\) is the size of the yield surface [21]. When, \(f = k\), yielding is supposed to have started and the surface corresponding to this function is known as the yield surface. It is also common to use effective stress and strain definitions based on the Mises yield criterion.

\[
\sigma_e = \frac{1}{\sqrt{3}} \sqrt{(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + 6\tau_{xy}^2 + 6\tau_{yz}^2 + 6\tau_{zx}^2} \tag{1.4}
\]

\[
\varepsilon_e = \frac{2}{\sqrt{3}} \sqrt{(e_x)^2 + (e_y)^2 + (e_z)^2 + \frac{(\gamma_{xy}^2 + \gamma_{yz}^2 + \gamma_{zx}^2)}{2}} \tag{1.5}
\]
Where,

\[ \sigma_x, \tau_{xy} = \text{normal and shear stress components}. \]

\[ e_x = \frac{1}{3} (2\varepsilon_x - \varepsilon_y - 2\varepsilon_z) = \text{deviatoric strain and is defined similarly for} \ e_y, e_z. \]

\[ \gamma_{xy} = 2\varepsilon_{xy} = \text{engineering strain} \]

Hardening in a material can be explained as the evolution of the yield surface. Hardening can be isotropic – yield surface expands but does not change its shape, kinematic – yield surface changes its location with no change in shape or size, and distortional – yield surface distorts. Difference in elastic-plastic and elastic-viscoplastic behavior is shown in Figure 1.11. Non-proportional loading paths occur as a result of change in the ratios of the principal stresses, or the rotation of the principal axes during a cycle, or a combination of both.

![Figure 1.11: Stress-strain response under cyclic loading. (a) Elastic-Plastic material. (b) Elastic-viscoplastic material [19].](image)
Chaboche has carried out pioneering work in the area of constitutive model development for cyclic plasticity and cyclic viscoplasticity [22]. This work was built on the previous work by Krempl, Mroz, Dafalias and Popov [23, 24, and 25]. Chaboche has compared different models like the Ohno-Kachi time independent plasticity theory, viscoplastic models by Walker and by Krempl and Yao and another by Watanabe and Atluri. These models validate the non-linear kinematic (NLK) hardening rule proposed by Prager and Armstrong and Fredrick [26]. These models incorporate different observed phenomena like isotropic hardening, plastic-strain range dependence and out of phase loading effects. The comparisons between these models also show that the NLK model is indispensable in correctly predicting the cyclic response of materials and that all the aforementioned models use it. However one of the major drawbacks of these models is that none of them could predict cyclic ratcheting.

Figure 1.12: (a) Stress-strain response with stable prehistory loading shown. (b) Ratcheting response shown for axial strain [27].
Material modeling of the cyclic properties of Inconel 718 has been further investigated by Chaboche and collaborators [27, 28]. Chaboche et al. have previously shown that plasticity analysis cannot be carried out based on their stabilized response for materials that soften cyclically. Also, many critical structural members fail through the accumulation of strain or ratcheting, rather than fatigue. In this paper, Chaboche has attempted to model this ratcheting behavior in Inconel 718 at elevated temperature (ratcheting response is shown in Figure 1.12).

A combination of primary constant and secondary cyclic load is required to model ratcheting. In uniaxial tests the primary load would be the mean stress and the secondary load is cyclic stress. In multiaxial tests, the primary load is a constant stress and the secondary load may be cyclic torsion. Equivalent stress condition between uniaxial and multiaxial tests is determined from Von Mises criterion. The multiaxial ratcheting is found to be lower than uniaxial ratcheting. The authors have proposed the use of a combination of both linear-kinematic and nonlinear-kinematic hardening for modeling the ratcheting effect. The non-linear-kinematic model is incorporated with a threshold limit for the dynamic strain recovery term which greatly improves the modeling of limited ratcheting. Cyclic response of the material also depended on the strain range and needs to be incorporated in the model. The stress-strain and ratcheting response is shown in Figure 1.13.
Hassan et al. have studied multiaxial time-independent ratcheting behavior of Carbon steel 1026 [29]. Tube specimens were subjected to constant internal pressure and cyclic, symmetric axial strain and stress control. The first set of axial strain control experiments led to ratcheting in the circumferential direction, whereas the second set of experiments led to ratcheting in both circumferential and axial direction. The experiments showed a constant rate of ratcheting. Then the Prager-Palgen, Dafalias-Popov and Tseng-Lee models were used to model this multiaxial ratcheting behavior. These models gave a good approximation in the trends of the material behavior but could not predict the rates of ratcheting correctly. The hardening rule used for predicting ratcheting made a significant difference in the simulation result. The best simulation was achieved with the Armstrong-Fredrick hardening rule as the others either predicted a higher rate of ratcheting or that ratcheting would be arrested after a few cycles. These discrepancies were attributed to the fact that the hardening rules assume that
the yield surface does not change its shape or size during multiaxial loading. Most constitutive models in the present literature have only been moderately successful in modeling multiaxial ratcheting. Some of the simulation results for different paths are shown below in Figure 1.14.

![Figure 1.14: Experiment and modeling data for ratcheting under different loading paths using the three-decomposed hardening law proposed by Chaboche implemented by Hassan et al. [21].](image)

Multiaxial ratcheting of medium carbon steel has been studied by Chen et al. [30], who have used a number of different loading paths to study the effect of loading paths and proportional loadings on the material, shown in Figure 1.15. Comparisons between different Ohno-Wang type kinematic hardening rules that are used to simulate the ratcheting behavior (shown in Figure 1.16) have been made and a new modified Ohno-Wang model has been proposed that is capable of simulating the ratcheting better. This model improves on the Ohno-
Wang model by attempting to modify the dynamic recovery term which depends on the co-axiality of the plastic strain rate and back stress. The only drawback that this model suffers from is that it requires a designer to determine additional material parameters.

Figure 1.15: Selective loading paths that are used to study ratcheting and effect of non-proportional loading on material behavior [30].
Figure 1.16: Improvement seen with the model developed by Chen et al. – each case is a particular loading path shown above [30].

An evaluation of various constitutive models to predict ratcheting has been carried out by Bari and Hassan [21] for carbon steel under uniaxial and biaxial loading histories. The models evaluated include Prager, Armstrong and Fredrick, Chaboche [31, 32], Ohno-Wang and Guionnet. The Prager law predicts that the hysteresis loop is bilinear as the yield surface moves linearly with plastic strain. The Prager model is unable to predict ratcheting and is found unsuitable for modeling the behavior of Inconel 617. The Armstrong-Frederick model improves the kinematic hardening rule by including a memory term which ensures that the change in the yield surface depends on the strain path. However, it is unable to produce a constant plastic modulus for experiments with a large strain range. The ratcheting simulation for most materials
through this model is not accurate but it provided the early motivation for developing a more non-linear kinematic hardening rule.

Chaboche improved this model by dividing the hysteresis curve into three parts. The first hardening rule models the onset of yielding, the second models the knee or non-linear portion and the third simulates the high strain range portion. This decomposition improves the ratcheting simulation of the hysteresis curve. This was improved by Chaboche [33] by including a fourth term with a threshold in the dynamic recovery or recall term in the kinematic hardening law. The modified Chaboche model predicts the ratcheting response much better and was further modified by Bari and Hassan. Other authors like Ohno-Wang have proposed decomposed models which simulate hysteresis curve closely but simulates ratcheting more than the observed experimental value. Similarly, other models like the Guionnet and the Dafalias-Popov model have their own advantages and disadvantages in predicting ratcheting under different loading histories.
Chapter 2

Experimentation

The mechanical behavior of materials is investigated by conducting uniaxial and less frequently, multiaxial experimentation. These experiments help researchers gain an in-depth understanding about the different physical phenomena that affect material performance. Viscoplastic materials will show creep, relaxation, hardening-softening, dynamic strain aging and many other phenomena. Also, the effect of fatigue loading must be understood for structural members. As explained in the Introduction, Inconel 617 in the intermediate heat exchanger (IHX) of high temperature reactors will experience uniaxial and multiaxial loads. The key objective of this research is to characterize mechanical behavior of Inconel 617 associated with the creep-fatigue and creep-ratcheting interactions.

High temperature, multiaxial experimentation is one of the most complex experimentation carried out to understand mechanical behavior. Several researchers have worked on elevated temperature testing and documented different techniques for carrying out these tests. The most complete experimental description has been provided by Ellis and Bartolotta [34], who have advocated the use of an adjustable coil fixture for induction heating. Such a fixture is convenient to use and provides access to the specimen surface. This facilitates the measurement of strain with the help of a high-temperature extensometer. An induction heater is used for heating the specimen to the test temperature. Lissenden et al. have studied the axial-torsional load effects on Haynes 188 at 650°C [35] and have explained the experimental procedure and instruments in good detail. Previous researchers like Totemeier, [17] Chen et al. [30] who have worked on elevated temperature testing have used similar kinds
of testing equipment to conduct uniaxial and multiaxial tests. Therefore, due to its widespread acceptability, an induction heating system with flexible coil fixture and water cooled grips has been adopted in this research. This chapter on experimentation has been divided into: specimen description, test equipment, experimental challenges, test matrix and data acquisition and analysis.

2.1 Specimen Description

The Inconel 617 material used for testing was shaped in the form of thin-walled tubular specimen. Coincidentally, the tubular specimens resemble the tubes of the IHX that will be under similar loading conditions. Also, since a test facility having an axial-torsion test rig is available, a tubular specimen is convenient to use. The specimens were machined from a 38 mm thick annealed plate with the axis of the specimen aligned in the rolling direction. The plate was fabricated from heat QA101053 (the chemical composition is provided in Table 2.1). Low stress grinding was used during the final machining. The fatigue specimens were machined at the Penn State Engineering Services Shop. The gage section has an external diameter of 21 mm and an internal diameter of 18 mm and has a total length of 305 mm. Refer to Figure 2.1 for more details. The end sections are 30 mm in diameter so that they can be gripped in the hydraulic collet grips without crushing the tube.
Figure 2.1: Tubular specimen with dimensions in mm.

Table 2.1: Composition in weight % for Inconel 617 used in this research [36]

<table>
<thead>
<tr>
<th>Element</th>
<th>Composition (wt %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni</td>
<td>Balance</td>
</tr>
<tr>
<td>Cr</td>
<td>21.9</td>
</tr>
<tr>
<td>Co</td>
<td>11.4</td>
</tr>
<tr>
<td>Mo</td>
<td>9.3</td>
</tr>
<tr>
<td>C</td>
<td>0.08</td>
</tr>
<tr>
<td>Fe</td>
<td>1.7</td>
</tr>
<tr>
<td>Al</td>
<td>1.0</td>
</tr>
<tr>
<td>Ti</td>
<td>0.3</td>
</tr>
<tr>
<td>Si</td>
<td>0.1</td>
</tr>
<tr>
<td>Mn</td>
<td>0.1</td>
</tr>
<tr>
<td>Cu</td>
<td>0.04</td>
</tr>
</tbody>
</table>

2.2 Test Equipment

Multiaxial experiments were conducted on an MTS 319 Axial Torsion test rig system with a ±245,000N axial and ±2830 N-m torsional capacity. The specimen is held in water cooled 646 hydraulic collet grips in the vertical direction. An MTS Flextest 40 controller is used to control the test rig and acquire data. The crosshead and the actuator in the test rig can be moved to accommodate the specimen within the grips. In a test, the actuator moves in displacement, load or strain control in either axial, torsion or combined directions to load the specimen. Multiple sensors like loads cells and linear-variable displacement transducers (LVDT) are attached on the crosshead and the actuator which measure load and displacement as well as torque and angle of twist during a test. The controller actuates based on a ±10 volts range.

The high-temperature biaxial extensometer MTS 632.68B-08, shown in Figure 2.2, was used to measure the axial and shear strains. Two ceramic rods protrude out of the
extensometer body and rest against micro-indents on the specimen surface. The ceramic rods are held in place by two leaf springs and this entire assembly is shielded from the heated specimen by a water-cooled shield (shown in Figure 2.3). The extensometer is also water cooled. The extensometer can be used up to a temperature of 1200°C and has an axial strain range of 10% and a shear angle of twist range of ±5°. The distance between the ceramic rods is 25.4 mm and is defined as the ‘gage section’ of the specimen for all measurements.

![MTS 632.68B-08 high-temperature biaxial extensometer.](image)

A 7.5 KW Ameritherm, radio-frequency induction heater is used to achieve the test temperatures of 850°C and 950°C. The induction heater sends out a high-frequency current to three coils that are mounted on an adjustable-positioning-mechanism rig similar to the one described by Ellis and Bartollota [34]. These coils induce eddy currents on the specimen surface and resistance in the specimen creates joule heating. Thermocouples were used to measure and control the test temperature (in °C). The temperature gradient is kept within ±1% of the
desired temperature as described in ASTM 606. This is described in more detail in the experimental preparation section.

The temperature was controlled with the help of an Omega CN77554 temperature controller. The controller was connected to the heater and regulated the amount of power that the heater supplied to the coil, thereby controlling the amount of heat that was supplied to the specimen. The controller could also send an output voltage to the Flextest 40 controller so that the specimen temperature could be stored along with other variables. However, this signal was encumbered by electronic noise.

Figure 2.3: The MTS 319 with specimen gripped and extensometer mounted.
Other test equipment used for the experiments includes a heat exchanger, which was used to supply cooling water to the heater. A temperature switch (Omega DP 7001) was used to interlock the top grip with the heater. This switch was interlocked with the heater and ensured that the grips were not heated above their maximum temperature of 66°C. A K-type temperature indicator with 8 channels and K-type thermocouples were used to read out the temperatures along the length of the specimen. The entire test assembly is shown in Figure 2.4.

Figure 2.4: MTS 319 Axial-Torsion test rig with ancillary instruments.
2.3 Experimental preparation and challenges

2.3.1 Temperature gradient measurement

The multiaxial high-temperature testing was carried out in conformance to ASTM E606-04. ASTM standards require a temperature distribution in the gage section of the specimen that cannot vary more than ±1% (on a Celsius scale). This task can be challenging at very high temperatures. Designing coils for elevated temperature testing takes considerable time and effort and the best coil design can be validated only by trial and error. Initial experimentation indicated that equal coil diameter were not effective in maintaining a uniform temperature distribution in the gage section of the specimen. Uniform temperature distribution is difficult to maintain as the center of the specimen is heated up to 850°C or 950°C by induction heating, whereas the ends of the specimen are gripped in water-cooled collet chucks. Therefore, slightly larger center coils were used which ensured a more uniform gradient. The upper and lower coils measure 35.6 mm and the middle coil is 39.4 mm in diameter. The optimum distance between each coil is 9.3 mm – 10.2 mm (0.375 in – 0.4 in). This spacing is difficult to judge and will greatly affect the temperature gradient in the specimen. If the spacing between the coils is larger than 10 mm, the temperature gradient will not be within the ±1% range. If the spacing is smaller, the ceramic probes/rods for the extensometer will touch the coils as the axial strain increases during the test. This could create additional problems as the test has to be interrupted and restarted.

In order to reach the set point temperatures of 850°C and 950°C, initially a 4-2-4 coil arrangement was used. However, after preliminary testing it was found that a portion of the specimen outside the gage section had necked during tensile loading at high temperature,
indicating that the specimen was overheated outside of the gage section. Thermocouples (TCs) were attached to this section and the temperature measured was 40°C above the set point temperature, and therefore an entirely new 3-2-3 design coil was created and used for heating the specimens.

The temperature of the specimen is measured using K type TC wires which are spot-welded to the specimen. K-type thermocouples were chosen as they work in the ~200°C to +1350°C range. K-type thermocouples use Chromel (90 % Nickel and 10% Chromium) and Alumel (95% nickel, 2% manganese, 2% aluminum and 1% silicon) wires. The grip temperatures are monitored by stick-on K-type thermocouples. Figure 2.5 shows a specimen gripped and heated up to a temperature of 950°C with the extensometer mounted.

Figure 2.5: Specimen heated up to 950°C. Ceramic blocks shielding the grips are visible in the figure.
The temperature distribution in the specimen was determined with the help of 8 TCs. The center TC was used to control the temperature of the specimen. This TC was connected to the controller whereas the other TCs were connected to the temperature indicator. The thermocouple numbering scheme is shown in Figure 2.6. 5 TCs, 6.35 mm apart were placed in the gage section, 2 were placed on the shoulder 38 mm away from the center and 1 TC was welded 180° rotated from the center TC. The five TCs in the center were used for accurate thermal gradient measurements in the gage section. The shoulder TCs were used to explore if the temperature could be controlled from that point. However, repeated thermal testing indicated that the shoulder temperatures did not give consistent readings relative to the control TC. Thus the entire test program was conducted with the center TC as the control TC. The TC 180° away from the center TC indicated that the temperature distribution in the circumferential direction was within the prescribed limits. Additionally, TCs were spot welded 25.4 mm away from the center TC and at 90° and 270° around the center TC to measure and validate the thermal gradient. These readings were consistent and were within the prescribed limits. Additionally, to ensure a better temperature distribution in the gage section, the set point temperature in the controller was kept 4-5°C higher than the test temperature. The temperature gradient is reported below in Table 2.2 and 2.3.
Figure 2.6: Thermocouple arrangement shown on the specimen. TC 8 is 180 degrees from TC 4.

Table 2.2: Temperature profile of the specimen at 850°C

<table>
<thead>
<tr>
<th>Thermocouple No.</th>
<th>Indicated Temperature in °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (Lower shoulder)</td>
<td>628</td>
</tr>
<tr>
<td>2</td>
<td>841</td>
</tr>
<tr>
<td>3</td>
<td>844</td>
</tr>
<tr>
<td>4 (Control TC)</td>
<td>855</td>
</tr>
<tr>
<td>5</td>
<td>841</td>
</tr>
<tr>
<td>6</td>
<td>843</td>
</tr>
<tr>
<td>7 (Upper shoulder)</td>
<td>645</td>
</tr>
<tr>
<td>8 (180° rotated away from the center TC)</td>
<td>854</td>
</tr>
<tr>
<td>9 (Lower Grip)</td>
<td>30</td>
</tr>
<tr>
<td>10 (Upper Grip)</td>
<td>46</td>
</tr>
</tbody>
</table>
Table 2.3: Temperature profile of the specimen at 950°C

<table>
<thead>
<tr>
<th>Thermocouple No.</th>
<th>Indicated Temperature in °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (Lower shoulder)</td>
<td>723</td>
</tr>
<tr>
<td>2</td>
<td>942</td>
</tr>
<tr>
<td>3</td>
<td>944</td>
</tr>
<tr>
<td>4 (Control TC)</td>
<td>955</td>
</tr>
<tr>
<td>5</td>
<td>943</td>
</tr>
<tr>
<td>6</td>
<td>943</td>
</tr>
<tr>
<td>7 (Upper shoulder)</td>
<td>756</td>
</tr>
<tr>
<td>8 (180° rotated away from the center)</td>
<td>955</td>
</tr>
<tr>
<td>9 (Lower Grip)</td>
<td>35</td>
</tr>
<tr>
<td>10 (Upper Grip)</td>
<td>57</td>
</tr>
</tbody>
</table>

At 950°C, the upper grip temperature was found to be higher than the recommended temperature for its safe operation. This is not surprising as there is a steep gradient between the center of the specimen, which is maintained at 950°C, and the grips which are water cooled. The maximum allowable temperature for the grips is 66°C. The grips have a specified maximum temperature as the oil in the seals, which help the grips function, could leak at high temperatures. This could cause the grips to fail, thwarting the test. In some experiments the grips temperature reached up to 70°C. Different alternatives were considered and ceramic insulation blocks were used as they are cost effective and easy to mount. The ceramic insulation brought down the temperature of the grips to 57°C for a test temperature of 950°C. A temperature switch was used to interlock the grips with the heater to provide an additional safety feature. An Omega DP 7001 temperature switch was interlocked with the heater. The temperature switch is a Single Pole Double Throw (SPDT) on/off type relay. The causes the
heater to shut off once the grip temperature exceeds 66°C. The ceramic insulation together with the temperature switch provided a good safety mechanism for protecting the grips.

Calibration of the test rig was undertaken by MTS personnel. The biaxial extensometer was calibrated at the MTS factory. The test rig was also checked for correct alignment between the crosshead and the actuator (but only visually). Any misalignment could introduce additional bending loads in the specimen.

### 2.3.2 Safety interlocks and Test Rig Tuning

The test rig was tuned so that the command and input signals are in good agreement with each other. An incorrectly tuned controller will apply load/displacement values that are different from the desired input values. It could also have large transients in the signal, causing instability in the test rig. The test rig can be tuned with an ‘Auto Tune’ option that is provided on the controller. However, the tuning provided by the ‘Auto Tune’ option was not adequate and a manual tuning was undertaken. The input and output values in load, displacement and strain were observed on a scope. Then the tuning parameters P (proportional), I (integral) and D (derivative) were changed till the input signal was within acceptable limits of the command signal.

The safety interlocks are crucial part of the MTS Axial-Torsion rig operations. The Ameritherm’s interlock circuit clears if all cooling water to the power supply and to the remote heating head is on and the MTS controller interlocks are clear. Once running, the Ameritherm’s internal interlocks (water flow and temperature controller set-points) and temperature control system function normally to operate and protect the Ameritherm and remote heating head.
without any effect on the MTS system. If the MTS interlocks come in - causing the hydraulics to shutdown, the Ameritherm heater’s interlock circuit trips. This ensures that when a specimen fails/fractures and the test ends, the heater switches off. If the heater does not switch off, it could overheat the fractured specimen causing it to melt and could potentially create a dangerous situation. Again, if the heater interlocks were to come on for any reason, it would cause the MTS loading program to stop. Testing the specimen while it is not at the set point temperature is not desired, this interlock ensures that in the event of the heater switching off, the test is stopped. A schematic for the interlocks and the wire connections are shown in Figure 2.7.

![Diagram](image)

Figure 2.7: Safety interlocks and wire connections for the MTS flextest and Ameritherm heater.
Care must be taken to ensure that the MTS servo-valves are cleaned regularly. Square-wave displacement signal and an angle wave signal are used for the valve cleaning. During the cleaning operation the dither amplitude is turned up. This creates a high pitch sound in the manifolds. This should be done for about 15-20 minutes and once a month to ensure that the manifold valves are not blocked by silt and dirt particles.

2.3.3 Extensometer vibration and signal noise

Problems were encountered while taking measurements with the extensometer. The biaxial extensometer is exceedingly sensitive to electronic noise and vibrations. Initial test conducted showed that strain-controlled tests were especially sensitive to the noise in the strain signal. Noise in the signal would cause the test control to become unstable and the test would have to be immediately stopped by pushing the emergency stops (e-stops). Noise can be introduced in the strain signals in various ways. The vibrations in the test rig or extensometer shield could introduce noise. Alternatively, if the axial and torsional extensometer wires touch each other or contact the moving actuator, it could cause the test to go unstable. Vibrations can also be introduced through the water-cooling tubing to the extensometer. Strain signals taken during a live test show that an optimal flow of 50 cc/min water should be maintained. Higher flow could induce higher vibrations and noise in the signal, whereas a low water flow level would not sufficiently cool the extensometer. Therefore, it is recommended that the wires and the cooling coils be restrained during any tests and especially during strain-control tests.

Another cause for concern was the high levels of noise in the axial load signal. Since, MR1 and MR2 experiments were conducted in axial-load and shear-strain control, high noise levels in
the axial load signal could affect the rate and measurement of the axial strain signal. This noise was traced to the radio-frequency heater current. Noise in the axial signal was found to increase with an increase in temperature as the radio-frequency heater supplied a higher voltage current to the coils at higher temperatures. Therefore, the axial and torsional load cables were provided with additional shielding and were grounded. The axial load signal improved and could be used as a control channel.

2.3.4 Experimental Procedure

An experimental procedure was developed so that the tests could be conducted in a systematic manner. This procedure is listed in order below:

1. The specimen is measured and all dimensions are recorded in the lab book. TC position are measured and marked and the TCs are carefully spot-welded to the specimen. The spot welder is set to pulse -1, polarity – straight, manual heat – 20 and channel M settings.

2. The 25.4 mm indenter is used to make indents in the middle of the specimen for the extensometer probes.

3. The process water lines should be on and all interlocks should clear on the Ameritherm heater. The hydraulic pump and manifolds are then started on the Flex Test controller through the software.

4. The load and torque values should be set to zero before the specimen is inserted in the hydraulic grips.
5. The temperature controller, interlock switch for the grips and all temperature indicator channels should be working.

6. The specimen is inserted in the coils while taking care not to damage the TC connections.

7. The MTS control should be in displacement control and is changed from exclusive to handset control so that the actuator motion can be controlled from the handset. The specimen is first inserted in the top grip and the actuator is moved up to the intended point. Specimen is then gripped and the control mode is changed to load and torque control and the load and torque values are adjusted to zero.

8. The extensometer is now ready to be mounted. First, the extensometer heat shield should be adjusted so that it has enough clearance for the probes to touch the specimen. Then the extensometer is mounted on the shield and is settled in to the indents.

9. The cooling lines to the extensometer need to be adjusted and it should be ensured that all the cooling lines and extensometer cables are restrained and do not move or vibrate during the test.

10. A very low magnitude cyclic axial-load and shear-torque program is run for 10 cycles to allow the probes of the extensometer to settle in the indents.

11. Now, the specimen can be heated up to the test temperature in load and torque control, with both held at zero. Once the specimen reaches the test temperature, it is held for 20 minutes prior to mechanical loading to allow the temperature distribution to stabilize.
12. Finally, the test program is loaded and the test is started. Test data are acquired to the flex test controller.

2.4 Test Type and Matrix

In order to study the creep-fatigue and creep-ratcheting interaction of Inconel 617, hybrid strain-controlled and stress-controlled tests were conducted. Two types of loadings are presented here: MR1 and MR2, which are briefly described here.

2.4.1 MR1 Test

The MR1 test involved applying a steady axial load and a cyclic shear strain on the specimen as shown in Figure 2.8. The steady axial load results in creep strain in the axial direction. The cyclic shear strain could create cyclic hardening or softening of the shear stress. Due to the plastic coupling, it could also lead to axial strain ratcheting. Axial strain accumulation with time and number of cycles is of great interest because it will play an important role in the ultimate life of the specimen. The strain-controlled, shear stress-strain hysteresis loops will provide additional information about the material behavior at elevated temperatures. Ratcheting will also depend on the mean stress and the loading proportionality of a test. The MR1 test has a lower degree of non-proportional loading since the axial stress is held constant while the shear strain is cycled. Four experiments were conducted for the MR1 kind of tests. Two experiments were conducted at 950°C at effective strain rates of 0.1%/s and 0.04%/s and another two tests were conducted at 850°C at effective strain rates of 0.1%/s and 0.04%/s. The fast and slow rates help us understand the effect of loading rate on the material behavior. The strain range for the
four tests is $\pm 0.002$ and the axial stress was held constant at 12 MPa. The loading path and control signals are shown in Figure 2.8 and 2.9 and Table 2.4 provides the MR1 loading parameters.

![Figure 2.8: MR1 test control variables and loading path.](image)

Figure 2.8: MR1 test control variables and loading path.
Figure 2.9: Axial stress and shear strain signals for MR1 test.

Table 2.4: MR1 Test parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steady Axial Stress ($\sigma_{xs}$)</td>
<td>12 MPa</td>
</tr>
<tr>
<td>Mean Effective Strain</td>
<td>0</td>
</tr>
<tr>
<td>Effective Strain range ($\varepsilon_e$)</td>
<td>$\pm 0.002$</td>
</tr>
</tbody>
</table>
2.4.2 MR2 Test

The MR2 test involved applying a cyclic axial load with mean stress and symmetric hold times as well as symmetric-cyclic shear strain on the specimen. This kind of a test path is called bow-tie or hourglass path as shown in Figure 2.10. Unlike the MR1 test where the steady axial stress results in creep, the cyclic axial stress with a non-zero mean stress in MR2 test results in ratcheting. Since the axial load is cyclic, fatigue damage could be more significant in these tests compared to MR1 tests. The cyclic shear strain could result in cyclic hardening or softening and also lead to axial strain ratcheting. The accumulation in axial strain due to ratcheting could decide the ultimate life of the specimen. The effect of temperature on the viscoplastic material behavior can be understood from the plastic strain range of the shear stress-shear strain hysteresis plots. The MR2 test has a higher degree of non-proportional loading as compared to the MR1 tests due to the bow-tie test path. The effect of higher-degree of non-proportional loading on the ratcheting behavior will be of great interest. Four experiments were conducted for the MR2 kind of tests. Two experiments were conducted at 950°C at effective strain rates of 0.1%/s and 0.04%/s and another two tests were conducted at 850°C at effective strain rates of 0.1%/s and 0.04%/s. The fast and slow rates help us understand the effect of loading rate on the material behavior. The effective strain range for the four tests was ±0.0018 to compensate for the increase in the axial stress range and so that the equivalent stresses are comparable with the MR1 type of testing. The minimum value of axial stress is 0 MPa, maximum 24 MPa and the mean value is 12 MPa. The control signals are individually shown in the Figure 2.11 below and Table 2.5 lists the MR2 test parameters. One MR2 cycle consists of two shear strain circuits and one axial stress circuit.
Figure 2.10: MR2 test control parameters and loading path.

Figure 2.11: Axial stress and shear strain wave signals.
Table 2.5: MR2 test parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Axial Stress ($\sigma_{xm}$)</td>
<td>12 MPa</td>
</tr>
<tr>
<td>Axial Stress range ($\sigma_{xc}$)</td>
<td>±12 MPa</td>
</tr>
<tr>
<td>Mean Effective Strain</td>
<td>0</td>
</tr>
<tr>
<td>Effective Strain range ($\varepsilon_c$)</td>
<td>±0.0018</td>
</tr>
</tbody>
</table>

2.5 Data Acquisition and Analysis

Test data were acquired and saved through the Flex Test 40 controller. The signals acquired were axial - displacement, strain and load, shear – angle, strain and torque, time and specimen temperature. These signals were converted to stress and strain values using Equations 2.1, 2.2 and 2.3 on MATLAB. A sample MATLAB code is attached in the appendix. The signals were acquired at a rate of 10 Hz (or more) so that sufficient data points could be used for plotting and understanding the material behavior. A sample test program is attached in the appendix.

The angle of twist for the extensometer and the cycle time were calculated so that the duration of the tests could be estimated. This helped plan and schedule the tests. Sample calculation for MF1 tests– symmetric-cyclic shear-strain cycle with steady axial stress is shown below.

The strain amplitude $\gamma_{x,y}/\sqrt{3} = 0.002$ and the steady axial stress $\sigma_x = 12$ MPa.

So,

$$\frac{\gamma_{x,y}}{\sqrt{3}} = 0.002, \text{ or } \gamma_{x,y} = 0.003464$$
The extensometer output for shear strain is the actual angle of twist, this relation is shown in Equation 2.1. The sketch below explains it in a pictographic manner. This needs to be back calculated using the relation:

\[ \gamma_{xy} = \frac{\theta \times R}{L} \]  \hspace{1cm} (2.1)

(Note: Can be written as the angle of twist and strain, as these values are very small and therefore, the tangent of the angle can be approximated by the angle)

Where,

\[ \theta = \text{angle of twist} \]

\[ R = \text{the outer radius of the specimen} \]

\[ L = \text{the gage length} = 25.4 \text{ mm} \]

\[ \gamma_{xy} = \text{shear strain} \]

Solving for \( \theta \),

\[ \theta \approx 0.48^\circ \]

Therefore, in order to simulate strain value of 0.002, the extensometer probes need to twist by 0.48 degrees.
The effective strain rates for the tests are specified as 0.1%/s and 0.04%/s.

The shear strain rate for the tests = (effective strain rate/$\sqrt{3}$)

Cycle time = $\frac{\gamma_{xy}}{\text{shear strain rate}}$

Total Cycle time for MR1 test, 0.1%/s effective strain rate = $0.002/0.001 \times 4 = 8$ seconds.

Total Cycle time for MR2 test, 0.1%/s effective strain rate = $0.0018/0.001 \times 8 = 14.4$ seconds.

Likewise, the axial loads were calculated from the stress and the specimen size using Equation 2.2.

$$\sigma_a = \frac{P}{A} \quad (2.2)$$

Where,

$\sigma_a$ = Axial Stress

$P$ = Applied Load in Newton/Pound

$A = \pi (R_o^2 - R_i^2)$ = Area of the tubular specimen

The shear stress values were calculated using the Equation 2.3:

$$\tau = \frac{T \times R_o}{J} \quad (2.2)$$

Where,

$\tau$ = shear stress at the outer radius

$T$ = Torque

$R_o, R_i$ = Outer and Inner radius.

$J = \pi \left( \frac{R_o^4 - R_i^4}{2} \right)$ = Polar moment of inertia for a concentric tube.
The test matrix for MR1 and MR2 tests is shown in Table 2.6.

Table 2.6: Matrix for MR1 and MR2 tests with specimen numbers and test conditions

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Spec. No</th>
<th>Avg ID (mm)</th>
<th>Avg OD (mm)</th>
<th>Type</th>
<th>Temp. (°C)</th>
<th>Axial Stress Rate (MPa/s)</th>
<th>Effective Strain Rate (%/s)</th>
<th>Cycle time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>17.88 (0.704)</td>
<td>17.89 (0.7045)</td>
<td>17.88 (0.704)</td>
<td>17.90 (0.7047)</td>
<td>17.88 (0.7039)</td>
<td>17.90 (0.7046)</td>
<td>17.88 (0.704)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20.93 (0.824)</td>
<td>21.01 (0.827)</td>
<td>20.98 (0.826)</td>
<td>21.03 (0.828)</td>
<td>20.95 (0.825)</td>
<td>21.03 (0.828)</td>
<td>21.01 (0.827)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MR1</td>
<td>MR1</td>
<td>MR1</td>
<td>MR1</td>
<td>MR2</td>
<td>MR2</td>
<td>MR2</td>
</tr>
<tr>
<td></td>
<td>900</td>
<td>850</td>
<td>950</td>
<td>850</td>
<td>950</td>
<td>850</td>
<td>950</td>
<td>850</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>6.67</td>
<td>6.67</td>
<td>2.67</td>
<td>2.67</td>
</tr>
<tr>
<td></td>
<td>0.1</td>
<td>0.1</td>
<td>0.04</td>
<td>0.04</td>
<td>0.1</td>
<td>0.1</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>8</td>
<td>20</td>
<td>20</td>
<td>14.4</td>
<td>14.4</td>
<td>36</td>
<td>36</td>
</tr>
</tbody>
</table>

The inner and outer diameters were measured at 3 spots along the gage length of the specimen and these values were averaged. The plots were made using MATLAB R2008 version. The MATLAB codes are attached in the appendix.
Chapter 3

Results and Discussion

The results for the MR1 and MR2 experiments at different temperatures and different strain rates are presented. The test matrix for the MR1 and MR2 tests are shown in Table 2.6 in the previous chapter. The MR1 tests are presented first, followed by the MR2 tests and then a comparison between the MR1 and MR2 test has been carried out. The test results include test parameters and observations, plots for the different response signals as well as post-test observations and analysis.

Initially, stress and strain data were collected at room temperature and at 950°C to compare and explore the amount of electronic noise in the data. In each case the specimen is gripped in load and torque control and commanded to stay at zero. The plots for stress and strain versus time at room temperature and at 950°C are shown in Figure 3.1-3.8. The plot for axial stress versus time shows that the variations in the axial stress signal increase at 950°C as compared to room temperature. The total variation in the axial stress at room temperature is approximately 0.15 MPa whereas at 950°C it is 1.5 MPa. This could be due to the thermal strain-induced stress or the electronic noise from the heater.
Figure 3.1: Axial stress versus time at room temperature.

Figure 3.2: Axial stress versus time at 950°C shows higher amount of electronic noise.

The shear stress signal is almost independent of temperature as shown in Figure 3.3 and 3.4. The total variation in the shear stress signal is approximately 0.4 MPa.
Figure 3.3: Shear stress versus time at room temperature.

Figure 3.4: Shear stress versus time at 950°C.

The axial strain versus time plot is shown in Figure 3.6 for room temperature and in Figure 3.7 for 950°C. The total variation in the axial strain signal at room temperature is 17 με, whereas at 950°C, it is 100 με.
The plot shows that the free thermal strain at 950°C is approximately 0.0154. The free thermal strain at 850°C was also recorded and measured 0.0137. This data is consistent with the data received from Idaho National Laboratory (research partner for this project).

![Graph of axial strain versus time at room temperature.](image1)

**Figure 3.5:** Axial strain versus time at room temperature.

![Graph of axial strain versus time at 950°C.](image2)

**Figure 3.6:** Axial strain versus time shows higher variation at 950°C.

The shear strain signal, shown in Figure 3.7 and 3.8 shows that the signal drifts at higher temperature compared to room temperature. The total variation at room temperature is 20 \(\mu\varepsilon\),
whereas at 950 °C, it is 70 $\mu$e. However, the shear strain test parameter is approximately 100
times larger than these variations.

Figure 3.7: Shear strain versus time at room temperature.

Figure 3.8: Shear strain versus time at 950°C.
3.1 MR1 loading type

3.1.1 Test 1: MR1, 950°C, 0.1%/s strain rate

Test Parameters and Observation: The first of the MR1 tests was started following the procedure outlined in the Experimentation chapter and was carried out on specimen 617-3 to show the effect of higher temperature and higher strain rate on material behavior. The set point temperature for this test was kept at 950°C. The test parameters are listed in Table 3.1.

<table>
<thead>
<tr>
<th>Test Description</th>
<th>MR1, 950°C, 0.1%/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant Axial Load</td>
<td>251 lb (1117 N)</td>
</tr>
<tr>
<td>Angle of Twist</td>
<td>±0.482 degrees</td>
</tr>
<tr>
<td>Rate of Angle of twist</td>
<td>0.241 deg/s</td>
</tr>
<tr>
<td>Cycles to failure</td>
<td>900 (failure due to crack)</td>
</tr>
<tr>
<td>Time to failure</td>
<td>120 minutes</td>
</tr>
</tbody>
</table>

During test setup, the ceramic insulators for the grip were being adjusted when the rig became unstable and emitted a high pitch noise. The emergency-stop was pressed and the pump hydraulics was turned off. The specimen was taken out of the grips and the axial-load tuning value was lowered. The test was then restarted without any problems. After the test ran for 695 cycles, the lower extensometer probe came very close to touching the lower heating coils, as the plastic strain accumulated in the axial direction. If the lower extensometer probe touches the induction coil, it could cause the test to become unstable as it is a strain-control
test. Therefore, the lower coils were moved down with the help of the adjustable rig to accommodate the increase in axial strain. This is not preferred as it may lead to a change in the temperature gradient on the specimen. The plot of the axial stress-shear strain for this test is shown in Figure 3.9. Note, that the plot shows shear strain and not effective strain. There is electronic noise in the axial stress signal as can be seen in Figure 3.10. The shear strain channel has very little noise or variations.

Figure 3.9: Plot of Axial Stress versus Shear Strain for test 1.

Figure 3.10: Axial stress and Shear Strain versus time shows the test control.
The shear strain signal in Figure 3.10 does not show the changes in shear strain over a single cycle as it is a plot over the total time period of the test. Therefore, this plot has been magnified to show the test control in Figure 3.11 below.

![Shear strain signal](image)

**Figure 3.11: Shear strain versus time for first few cycles to show test control in finer detail.**

After 800 cycles, some acoustic noise was heard by un-aided ear, coming from the specimen at extreme angles of twist. This noise was not be measured or quantified, but could possibly be associated with crack growth and crack surface sliding. The specimen fractured at 900 cycles or approximately 2 hours of testing.

**Material Behavior:** The material behavior is characterized by the ratcheting and creep strain which accumulated in the axial direction and the shear stress-shear strain hysteresis loops. The axial-strain versus time and number of cycles is plotted in Figure 3.12. At 800 cycles, the axial strain data spreads into a broad line from the initial thin line. This might be associated with the point of macro-crack initiation. Once the crack started growing, it could have caused the axial strain to oscillate every cycle. Therefore, although the strain continued to increase, the data
spreads out into a broad line. This is shown in more detail by comparing the plots in Figure 3.13 and 3.14. The axial strain at the end of the test is measured to be approximately 0.055.

Figure 3.12: Axial strain versus time and cycles shows linear increase in axial strain accumulation.

Figure 3.13: Axial strain versus time shown in greater magnification.
Positions on the axial stress versus shear strain (Figure 3.9) and the corresponding positions on the axial strain versus time plot is marked on Figure 3.13. The increase in the shear stress as the shear strain cycles between maximum and minimum causes an increase in the axial strain accumulation. At the start of the test, there is an increase in the axial strain as the axial stress is increased. Once, the shear strain cycles from point B to C, the axial strain increases. From position C to B, there is slight decrease in the axial strain due to the decrease in the shear stress as the shear strain decreases to zero. Axial strain increases from position B to D as the effective shear stress increases (the shear strain cycles to minimum). The axial strain versus time plot in Figure 3.13 shows that there the axial strain signal oscillates per cycle. This could be due to the plastic coupling with the shear strain that is in cyclic control or it could be an artifact of the posited macro-crack on the extensometer measurement.

![Graph showing axial strain versus time](image)

**Figure 3.14:** Axial strain versus time towards the end of the test shows increase in axial strain range per cycle due to possible macro crack growth.

The axial strain signal shows nearly linear increase with time as shown in Figure 3.12. This strain is associated with both creep and ratcheting strain. The maximum-minimum cyclic shear stress versus number of cycles is shown in Figure 3.15. The plot shows rapid initial
softening over the first 10 cycles followed by a more stabilized behavior, and then there is a sharp reduction in stress range after 800 cycles.

Figure 3.15: Shear stress versus number of cycles shows the softening behavior at 950°C and faster rate.

This sharp reduction in the shear stress towards the end of the test could be associated with crack propagation. The shear stress at the beginning of the test is 111 MPa. A definitive failure criterion needs to be established for these tests. Other authors investigating Inconel 617 like Carroll et al. [36], have defined failure as 20% reduction in the maximum-minimum shear stress. However, such a definition of failure is difficult for our experiments as shear stress softens by widely varying amounts for the different tests. After 800 cycles the shear stress had softened to 70% of the maximum.

The shear stress versus shear strain plot in Figure 3.16 shows wide hysteresis loops indicating significant plastic strain. The plot for shear stress versus shear strain has been shown for cycles 1, 2, 4, 6, 8, 10, 20, 40, 60, 80, 100, 200, 400, 600, 800, 1000, 2000 and the last cycle (the same procedure has been followed for presenting the other test results). The plastic strain can be characterized by the width of the hysteresis loops. The strain at zero stress indicates the amount of plastic strain in the material. The plastic strain range (at zero stress) is 0.00446 rad
and shear stress range at zero strain is ±75.5 MPa (extreme cycles on the plots are considered for calculating this value for all the tests presented).

Figure 3.16: Shear stress versus shear strain.

Post Test Observation: At failure, the test rig emitted a high pitch noise and became unstable. The angle interlocks set at ± 10 degrees, caused the test to stop. The specimen was then put in zero load and torque control and the specimen was allowed to cool down to room temperature. A large transverse crack is present as shown in Figure 3.17. It formed outside the gage section – about 7.5 mm below the bottom indent for the extensometer rod. The crack was not visible during the test because it was hidden by the lower induction coil.

Figure 3.17: Specimen after failure - large lateral crack visible.
3.1.2 Test 2: MR1, 850°C, 0.1%/s strain rate

Test Parameters and Observation: This test was conducted to show the effect of lower temperature and higher strain rate on material behavior. The test was conducted in accordance with the previously described test procedure and with the test parameters listed in Table 3.2. Test was conducted on specimen 617-4 and the temperature set point for the test was 856°C. The axial load interlocks caused the test to shut down when the specimen was being gripped. This was because the axial load starts to increase as the specimen is gripped and the controls are changed from axial displacement to axial load. The test ran for 1350 cycles (3 hrs) on day 1 and was interrupted at the end of the day. On the second day, the control TC came off after 860 cycles. This was observed after 890 cycles and the test was immediately switched off at this point. Therefore, for 30 cycles, the test ran at a temperature lower than 850°C. The test was again restarted with a new TC and indents as the earlier indents were no longer in plane and could not be used for strain measurements. The test ran for an additional 1560 cycles on day 2 before the specimen failed.

Table 3.2: Test parameters for Test 2

<table>
<thead>
<tr>
<th>Test Description</th>
<th>MR1, 850°C, 0.1%/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant Axial Load</td>
<td>256.3 lb (1140 N)</td>
</tr>
<tr>
<td>Angle of Twist</td>
<td>±0.48 degrees</td>
</tr>
<tr>
<td>Rate of angle of twist</td>
<td>0.24 deg/s</td>
</tr>
<tr>
<td>Cycles to failure</td>
<td>3770 (failure due to cracks)</td>
</tr>
<tr>
<td>Time to failure</td>
<td>502 minutes</td>
</tr>
</tbody>
</table>
The plots were created from the combined data i.e. the data for both the days have been plotted together. The axial load and shear strain signals during the test is shown in Figure 3.18.

![Axial Stress versus Shear Strain](image)

**Figure 3.18: Axial stress versus shear strain.**

**Material Behavior:** The material displayed more elastic response at this temperature as compared to the previous test at 950°C. As shown in Figure 3.19, the axial strain ratcheted more slowly and material life was longer than the specimen tested at 950°C. The axial strain value measured at the end of the test is 0.0533. It is also reassuring to note that the material behavior after the test interruption is comparable to its behavior before the interruption.
The maximum-minimum shear stress versus number of cycles (Figure 3.20) shows an initial hardening for 50 cycles, which is then followed by softening behavior. This is different from the MR1 test conducted at 950°C. Also, note that there is a slight hardening observed when the test was restarted on day 2. The maximum shear stress is 145 MPa and it softened to 90% of this value (130 MPa) by the end of the test.

Figure 3.20: Shear stress versus shear strain shows the cyclic hardening-softening effect.
The shear stress-shear strain plot in Figure 3.21 shows that the maximum plastic strain range (at zero stress) was approximately 0.00317.

![Shear Stress vs Shear Strain](image)

**Figure 3.21**: Shear stress versus shear strain.

**Post Test Observation**: The test went unstable and the angle interlocks caused the hydraulic pump to turn off. The interlocks were reset and the specimen was cooled in zero load and torque control. The specimen was taken out from the grips and it was found that diagonal cracks oriented at 45° (see Figure 3.22) had developed in the center of the gage section.

![Multiple Angle Cracks](image)

**Figure 3.22**: Multiple angle cracks observed on the specimen surface.
3.1.3 Test 3: MR1, 950°C, 0.04%/s strain rate

Test Parameters and Observation: The objective of this test was to show the effect of higher temperature and lower strain rate on material behavior. The test was conducted on specimen 617-5 and the control TC was maintained at 955°C. The test parameters are shown in Table 3.3 below. On the first day, the test was stopped at 760 cycles or 4.25 hrs, as the axial strain had increased to 5.5%. The extensometer probe was close to touching the lower heating coils and therefore the test could not be continued. The specimen was cooled in zero load and torque control and then inspected. Slight necking was observed in the gage section, but no measurements were made. New indents were made about 45 degrees away from the old indent location and test was restarted on Day 2. The test ran for another 540 cycles (3.0 Hrs) and the axial strain increased an additional 8%. The test was stopped as the lower extensometer probe was again close to touching the lower coil.

Table 3.3: Test parameters for Test 3

<table>
<thead>
<tr>
<th>Test Description</th>
<th>MR1, 950°C, 0.04%/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant Axial Load</td>
<td>255 lb (1134 N)</td>
</tr>
<tr>
<td>Angle of twist</td>
<td>±0.4805 degrees</td>
</tr>
<tr>
<td>Rate of angle of twist</td>
<td>0.0961 deg/s</td>
</tr>
<tr>
<td>Cycles to failure</td>
<td>1300 (failure due to necking)</td>
</tr>
<tr>
<td>Time to failure</td>
<td>434 minutes</td>
</tr>
</tbody>
</table>
The axial stress versus shear strain is shown in the Figure 3.23.

![Figure 3.23: The axial stress versus shear strain signal during the test.](image)

**Material Behavior:** The axial strain versus time and number of cycles plot is shown in Figure 3.24. This plot has been made by combining the data from both days. It is interesting to note that that the axial strain accumulation is different for both the two days. This could possibly be due to necking/deformation at the end of the first day of testing. At the end of day 1, the axial strain had increased to 0.055. On subsequent testing, this localized deformation increased at a greater rate. Therefore for modeling and analysis purposes, perhaps only the data from day 1 should be used. Failure can be defined as the necking observed at the end of day 1 testing. However, for the sake of completeness the data for the next day is also presented. The total axial strain increased to 0.13 by day 2 but the specimen did not have any visible cracks.
The maximum-minimum shear stress versus number of cycles plot shows gradual softening till failure. The maximum stress at the start of the test is 103 MPa and the peak shear stress drops to 80% of the maximum stress by 345 cycles. The specimen softened by 54% by the end of the test to 56 MPa.

Figure 3.25: Shear stress versus cycles shows gradual softening behavior of Inconel 617.
The shear stress–shear strain loops, shown in Figure 3.26, show the amount of plastic strain present in the material. The softening behavior of the material is also clearly shown by the higher initial stress curve and the gradually decreasing stress range. The maximum plastic strain range (at zero stress) is 0.0045 rad and the maximum stress value at zero strain is 71.6 MPa.

**Figure 3.26: Shear stress versus shear strain hysteresis loop.**

**Post Test Observation:** The specimen was cooled in zero load and torque control and inspected at the end of day 2. The specimen had substantially necked in the gage section as it can be clearly seen in Figure 3.27. Measurements of the specimen outer diameter were made after the test to quantify the amount of necking that occurred in the gage section. This is listed out in Table 3.4. The maximum change in the diameter measured 8%. 
Figure 3.27: Necking observed in the specimen after test 3.

Table 3.4: Change in the outer diameter of the specimen at the end of test 3

<table>
<thead>
<tr>
<th>Position</th>
<th>Outer Diameter (mm) – Initial Diameter:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20.98 mm</td>
</tr>
<tr>
<td>12.7 mm away from center towards top</td>
<td>20.57</td>
</tr>
<tr>
<td>6.35 mm away from center towards top</td>
<td>20.27</td>
</tr>
<tr>
<td>Center</td>
<td>19.43</td>
</tr>
<tr>
<td>6.35 mm away from center towards bottom</td>
<td>19.86</td>
</tr>
<tr>
<td>12.7 mm away from center towards bottom</td>
<td>20.7</td>
</tr>
</tbody>
</table>
3.1.4 Test 4: MR1, 850°C, 0.04%/s strain rate

**Test Parameters and Description:** This test explores the effect of lower temperature and lower strain rate on the material behavior. The test was conducted on specimen 617-6 and the control TC was maintained at 855°C. The test parameters are listed in Table 3.5. The test was interrupted after 2130 cycles on Day 1 as the axial strain increased to 4.0% and the lower extensometer probes were close to touching the coils. New indents and TC connections were made 45 degrees from their initial locations and the test was restarted on Day 2. Since a heavy oxide layer had formed on specimen at the end of day 1, the specimen was cleaned with 180 grit emery cloth so that the new TC connections could be made. On day 2, the test ran for an additional 1100 cycles and the axial strain increased by 2%. At the end of the test, the torque level decreased substantially and eventually the test rig went unstable and emergency stop was pushed.

<table>
<thead>
<tr>
<th>Test Description</th>
<th>MR1, 850°C, 0.04%/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant Axial Load</td>
<td>258 lb (1148 N)</td>
</tr>
<tr>
<td>Angle of twist</td>
<td>±0.4794 degrees</td>
</tr>
<tr>
<td>Rate of angle of twist</td>
<td>0.0958 deg/s</td>
</tr>
<tr>
<td>Cycles to failure</td>
<td>3230 (failure due to crack)</td>
</tr>
<tr>
<td>Time to failure</td>
<td>1077 minutes</td>
</tr>
</tbody>
</table>
The axial stress versus shear strain is shown Figure 3.28.

Figure 3.28: Axial stress versus shear strain.

**Material behavior:** The plot for axial strain versus time and number of cycles is shown in Figure 3.29. The plot has been made by combining the data for both the days. The axial strain plot for test 4 is very interesting as it shows two different rates of axial strain accumulation. There is an initial higher rate of increase followed by a lower rate of increase in the strain signal. This behavior is displayed in the plot for days 1 and 2. In day 2, the initial higher rate is not as pronounced. This curve resembles creep curves that have distinct primary and secondary creep regions. Creep could be more dominant for test 4 but this cannot be confirmed. A repeat test and additional creep-only tests should be carried out to investigate this behavior in the future.
Figure 3.29: Axial strain versus time and number of cycles.

The plot for maximum-minimum shear stress versus number of cycles is shown in Figure 3.30. The material shows hardening during the first 40 cycles and then gradually softens. The hardening is also clear in the initial cycles for day 2 test. The maximum shear stress is 140 MPa and it softens to 80% of the maximum by 3210 cycles. The peak shear stress softens by 60% of the maximum stress (80 MPa) by the end of the test.

Figure 3.30: Shear stress with number of cycles.
The shear stress-strain plot for test 4 is shown in Figure 3.31. The stress at zero strain is \( \pm 90 \text{ MPa} \) and the plastic strain range (at zero stress) is 0.00346.

**Figure 3.31: Plot for shear stress versus shear strain.**

**Post Test Observation:** The specimen was cooled in zero load and torque control and was inspected for cracks. A large angular crack had formed in the gage section and seemed to have started behind the specimen (180 degrees opposite the extensometer probes). Smaller cracks can be seen branching out from the main crack in Figure 3.32.

**Figure 3.32: Crack growth for 617-6 after the completion of test 4.**
3.1.5 Comparison between MR1 tests

Axial Strain versus cycles: The axial strain versus number of cycles and time plot is shown in Figure 3.33 (a) and (b) for tests 1-4. The effect of temperature on rate of ratcheting is clearly observed in the plot. The accumulation of axial strain is significantly greater at 950°C compared to 850°C. The plot also shows the effect of loading rate on the strain accumulation. The slower loading rate tests have more axial strain accumulation and a higher strain accumulation rate compared to the faster loading rate experiments. However, axial strain accumulation over time is much greater for test 1 – 950°C, 0.1%/s compared to test 3 – 950°C, 0.04%/s. However, for the 850°C tests, the axial strain accumulation is initially greater for the 0.04%/s test. The strain accumulation slows down for the 0.04%/s test till the strain accumulation in the 0.1%/s test surpasses it. The total strain accumulation is greater for the 0.04%/s test as compared to the 0.1%/s test.
Figure 3.33: Axial strain versus number cycles (a) and time (b) for tests 1-4 shows the comparison between the strain accumulation for different tests.
**Shear stress versus number of cycles:** The maximum-minimum shear stress versus number of cycles plot for the MR1 test is shown in Figure 3.34. The effect of temperature on cyclic hardening-softening behavior is clear from the plot. The shear stress values are much higher for the 850°C tests compared to the 950°C tests. The effect of loading rate can also be seen from the combined plot. The slower loading rate led to a lower shear stress compared to the higher loading rate for both the set of experiments at the two different temperatures. Softening rates are reasonably equal at 950°C and 850°C. At 850°C, we observe, cyclic hardening over the first few initial cycles whereas at 950°C, we observe gradual cyclic softening.

*Figure 3.34: Combined plots for shear stress versus number of cycles for MR1 experiments.*
**Shear stress versus shear strain**: The shear stress-shear strain plots for the four tests are shown in Figure 3.35. Only the first and the last hysteresis loops are included in these plots. The plots indicate the amount of plastic strain that is present in the material at zero stress. These values have been reported in the individual test results before. Comparison between tests at common strain rate clearly shows that the plastic strain range (zero stress) at the 950°C test is greater compared to the 850°C test. However, comparison between tests at common temperature shows that the loading rate does not seem to affect the plastic strain range (at zero stress) for a particular temperature, as it is observed in the plots below.
Figure 3.35: Shear stress versus shear strain comparison plots for MR1 tests.
3.2 MR2 loading type

MR2 tests investigate the effect of loading path on the material behavior. The MR2 tests have a higher degree of loading non-proportionality. Unlike the MR1 test, the axial load in MR2 test is also cycled with hold periods at the maximum and minimum stress levels. The MR2 have been discussed in greater detail in the previous chapter.

3.2.1 Test 5: MR2, 950°C, 0.1%/s strain rate

Test Parameters and Description: The first MR2 test was conducted on specimen 617-7 to show the effect of higher temperature and higher strain rate on material behavior. The test parameters are listed in Table 3.6. The effective strain amplitude is 0.0018 for all the MR2 tests. The test was stopped at 445 cycles as the axial strain increased to 3.0% and the lower extensometer probes were close to touching the coils. The coils were moved down slightly so that the probes had more space to move. Since the specimen was not taken out of the grips, it could not be checked for cracks. The test was restarted and the axial strain increased an additional 1%. The specimen failed after an additional 123 cycles and angle interlocks, set at ±10°, caused the test to stop.
Table 3.6: Test parameters for Test 5

<table>
<thead>
<tr>
<th>Test Description</th>
<th>MR2, 950°C, 0.1%/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial Load Amplitude</td>
<td>±252.72 lb (1124 N)</td>
</tr>
<tr>
<td>Mean Axial Load</td>
<td>252.72 lb (1124 N)</td>
</tr>
<tr>
<td>Axial loading rate</td>
<td>140.4 lb/s (624 N/s)</td>
</tr>
<tr>
<td>Angle of twist</td>
<td>±0.4331 degrees</td>
</tr>
<tr>
<td>Rate of Angle of twist</td>
<td>0.2406 deg/s</td>
</tr>
<tr>
<td>Cycles to failure</td>
<td>568 (failure due to crack)</td>
</tr>
<tr>
<td>Time to failure</td>
<td>136 minutes</td>
</tr>
</tbody>
</table>

The axial stress-shear strain signal is shown in Figure 3.36. The different positions on the bow-tie path are marked by alphabets A, B, C, D, E and F. A is the starting position and the successive alphabets show the path traversed in the axial stress – shear strain space.

![Figure 3.36: Axial stress versus shear strain shows the test control.](image)
The axial stress and shear strain signals with respect to time are plotted in Figure 3.37 and show that the signals were well controlled. As reported in previous MR1 tests, the axial load signal has some electronic noise from the radio-frequency heater current. The shear strain versus time plot has many cycles and appears continuous over a large time period. The signals are re-plotted in Figure 3.38 for the initial 300 seconds of the test.

Figure 3.37: Axial stress and shear strain signals with respect to time.

Figure 3.38: Axial stress and shear strain versus time magnified plots show the cyclic control.
Material Behavior: The axial strain signal is plotted in Figure 3.39 and shows a slight discontinuity at the point where the test was interrupted. The increase in axial strain appears to be linear and the axial strain at the end of the test is 0.038. There are some oscillations at the end of the test, which are most likely due to the macro-crack growth in the specimen.

A zoomed-in view of the axial strain versus time is shown in Figure 3.40. The axial strain signal has a repeating double saw-tooth feature. There is smaller and a larger tooth (marked in Figure 3.40). This feature was investigated in greater detail by comparing the peaks and valleys of the double saw-tooth with the axial stress and shear strain versus time plot. The various positions of the bow-tie path (marked in Figure 3.36 as A, B, C, D, E and F) and their corresponding position on the axial strain versus time plot have been marked on Figure 3.40. Position A is the start of the test. Position B marks the start of the bow-tie path. Position C is the shoulder of the larger tooth as the increase in the axial stress causes the axial strain to increase and due to plastic coupling with the shear strain. Position D is the peak of the larger tooth. From
position C to D, the axial stress is constant but the shear strain increases from maximum to minimum. This increase in the axial strain from C to D could be due to a combination of creep (from the constant axial stress) and ratcheting (from the plastic coupling between axial and cyclic-shear strain). Position E marks the valley of the larger tooth as the axial stress decreases from maximum to minimum. Position F marks the peak of the smaller saw-tooth. From position E to F, the axial stress is held constant at zero stress whereas the shear strain is cycled from maximum to minimum. Therefore, the increase in the axial strain from E to F could be primarily due to ratcheting as creep cannot be expected to play a significant role. After position F, there is again a slight decrease in the axial strain. As the shear strain is cycled from minimum to zero, it causes the effective shear stress to decrease by a larger amount as compared to the increase in the axial stress. This could cause the plastic strain vector to change its direction (in the equivalent strain space) and therefore, the plastic strain decreases from F to B.
Figure 3.40: Axial strain versus time signal magnified to show the axial strain cycling – positions on the bow-tie loading path and their corresponding positions on the axial strain sign.

The axial stress, axial strain, shear stress and shear strain signals are plotted with time and the corresponding positions A, B, C, D, E and F on the bow-tie path are marked on Figure 3.41.
Figure 3.41: Axial stress, axial strain, shear stress and shear strain versus time shown for 1 cycle – positions A, B, C, D, E, and F on the axial stress versus shear strain plot is marked here.
The maximum-minimum shear stress versus number of cycles is shown in Figure 3.42. The maximum shear stress is 107.6 MPa and softens by 90% to 89 MPa by 565 cycles. The shear stress exhibits a gradual cyclic softening behavior. There is also a small kink (stress drop) in the plot in the first initial cycles. This stress drop could not be attributed to any particular phenomena.

![Figure 3.42: Shear stress versus number of cycles.](image)

The shear stress-strain plot is shown in Figure 3.43. The maximum plastic strain range (at zero stress) is 0.003468 and at zero strain, the shear stress at zero strain is ±63 MPa.
The axial stress versus axial strain plot is shown in Figure 3.44. This plot has been shown for cycles 2 and 200 for all the MR2 tests. The axial strain increases as the axial stress increases and also, when the axial stress is held steady.
Table 3.7: Axial strain maximum-minimum values over cycle number.

<table>
<thead>
<tr>
<th>Cycle Number</th>
<th>$\varepsilon_{\text{max}}$</th>
<th>$\varepsilon_{\text{min}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.0006814</td>
<td>0.0002877</td>
</tr>
<tr>
<td>20</td>
<td>0.001901</td>
<td>0.001488</td>
</tr>
<tr>
<td>200</td>
<td>0.01391</td>
<td>0.01352</td>
</tr>
<tr>
<td>567 (second last)</td>
<td>0.03874</td>
<td>0.03776</td>
</tr>
</tbody>
</table>

Post Test Observation: A large crack had formed outside the gage section, 7.6 mm above the top extensometer probe indent as shown in Figure 3.45.

Figure 3.45: Crack observed in specimen 617-7 after test 5.
3.2.2 Test 6: MR2, 850°C, 0.1%/s strain rate

**Test Parameter and Description:** This test was conducted on specimen 617-8 to show the effect of lower temperature and higher strain rate on material behavior. The test parameters and the axial stress-shear strain signals are shown below in Table 3.8 and Figure 3.46. The test ran into problems when it was started the first time. The heater switched off after 28 cycles as the laboratory circuit board fuse switch had tripped. The test stopped as the temperature interlocks prevent a test from running below its set point temperature. The extensometer was removed and the specimen was cooled. The interlocks were reset and the test was restarted. The same indents and thermocouple connections were used for conducting the restarted test, which ran for 2219 cycles (approximately 9 hours). The axial strain had increased to approximately 5% by the end of the test.

**Table 3.8: Test parameters for Test 6**

<table>
<thead>
<tr>
<th>Test Description</th>
<th>MR2, 850°C, 0.1%/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial Load Amplitude</td>
<td>±257.4 lb (±1145 N)</td>
</tr>
<tr>
<td>Mean Axial Load</td>
<td>257.4 lb (1145 N)</td>
</tr>
<tr>
<td>Loading rate</td>
<td>143 lb/s (636.1 N/s)</td>
</tr>
<tr>
<td>Angle of Twist</td>
<td>±0.4317 degrees</td>
</tr>
<tr>
<td>Rate of Angle of twist</td>
<td>0.2398 deg/s</td>
</tr>
<tr>
<td>Cycles to failure</td>
<td>2247 (failure due to cracks)</td>
</tr>
<tr>
<td>Time to failure</td>
<td>540 minutes</td>
</tr>
</tbody>
</table>
Material Behavior: The axial strain versus time and number of cycles is plotted in Figure 3.47. The axial strain increases continuously but with a decreasing rate. This is unlike the axial strain data for MR1 test at 850°C and 0.1%/s strain rate, where axial strain increase was nearly linear over time. The axial strain at the end of the test measured 0.0515.
The maximum-minimum shear stress versus number of cycles, shown in Figure 3.48 shows a hardening behavior in the first 80-90 cycles followed by a gradual softening behavior. Since this test was conducted at 850°C, the stress values are higher compared to test 5. The maximum shear stress is 140 MPa and it cyclically softens to approximately 85% of the maximum by the end of the test.

![Graph showing shear stress versus number of cycles](image)

*Figure 3.48: Shear stress versus number of cycles shows gradual softening behavior.*

The shear stress-strain plot is shown in Figure 3.49 below. The stress values at zero strain are ±72.3 MPa and the maximum plastic strain range (at zero stress) is 0.00228 radians.
The axial stress versus axial strain plot is shown in Figure 3.50. The axial strain cycles as the axial stress is in cyclic control. There is also an increase in the axial strain as the axial stress is held constant. The maximum-minimum axial strain for selective cycles is shown in Table 3.9.

Figure 3.49: Shear stress versus shear strain.

Figure 3.50: Axial stress versus axial strain.
Table 3.9: Axial strain maximum-minimum values over cycle number.

<table>
<thead>
<tr>
<th>Cycle Number</th>
<th>$\varepsilon_{\text{max}}$</th>
<th>$\varepsilon_{\text{min}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.0004636</td>
<td>0.000033</td>
</tr>
<tr>
<td>20</td>
<td>0.0009487</td>
<td>0.0005039</td>
</tr>
<tr>
<td>200</td>
<td>0.005726</td>
<td>0.0053</td>
</tr>
<tr>
<td>2000</td>
<td>0.04703</td>
<td>0.04667</td>
</tr>
<tr>
<td>2246 (second last)</td>
<td>0.0515</td>
<td>0.05115</td>
</tr>
</tbody>
</table>

**Post Test Observation:** A large transverse crack formed outside the gage section as shown in Figure 3.51. It had formed 7.6 mm away from the top extensometer probe on the specimen. The position of the crack was similar to that in test 5. There were also multiple smaller cracks all along the length of the specimen.

![Figure 3.51: Transverse crack in the specimen at the end of the test 6.](image-url)
3.2.3 Test 7: MR2, 950°C, 0.04%/s strain rate

Test Parameters and Description: This test was conducted on specimen 617-9 to show the effect of higher temperature and lower strain rate on material behavior. The test parameters are listed in Table 3.10. The test ran into problems as soon as the heater was started. On starting the heater, the test rig went unstable and it emitted a high pitch noise. The E-stop was pressed and the test was switched off. The test was restarted with the same indents and thermocouple connections. This test ran for 274 cycles or approximately 2.75 hours and was switched off as the specimen had undergone excessive deformation. The axial strain had increased to 6% by the end of the test and the gage section of the specimen had undergone localized deformation and necking.

<table>
<thead>
<tr>
<th>Test Description</th>
<th>MR2, 950°C, 0.04%/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial load amplitude</td>
<td>±256.7 lb (±1142 N)</td>
</tr>
<tr>
<td>Mean axial load/stress</td>
<td>256.7 lb (1142 N)</td>
</tr>
<tr>
<td>Axial loading Rate</td>
<td>57 lb/s (253 N/s)</td>
</tr>
<tr>
<td>Angle of twist</td>
<td>±0.4321deg</td>
</tr>
<tr>
<td>Rate of angle of twist</td>
<td>0.0960 deg/s</td>
</tr>
<tr>
<td>Cycles to failure</td>
<td>274 (failure due to localized deformation)</td>
</tr>
<tr>
<td>Time to failure</td>
<td>164 minutes</td>
</tr>
</tbody>
</table>

The axial stress-shear strain signal for the test is shown in Figure 3.52.
Material Behavior: The axial strain versus time and number of cycles plot is shown in Figure 3.53. The axial strain increased to approximately 0.06 in 164 minutes. However, it is important to note that there were no cracks observed on the specimen and the test was stopped as the specimen had failed due to excessive deformation. This was very similar to test 3 (MR1, 950°C, 0.04%/s). Both the specimens experienced excessive deformations.

Figure 3.52: Axial stress versus shear strain shows the test control signals for the test.

Figure 3.53: Axial strain versus time and number of cycles.
The maximum-minimum shear stress versus number of cycles for the test is shown in Figure 3.54. The shear stress plot shows a sharp drop in the shear stress range initially and then a gradual cyclic softening behavior that is similar to test 3 (MR1, 950°C, 0.04%/s). The maximum shear stress is 99 MPa and it softens to 80% of the maximum stress by 123 cycles. The shear stress at the end of the test is 73% of the maximum value.

![Shear stress versus number of cycles](image1)

**Figure 3.54: Shear stress versus number of cycles.**

The shear stress versus shear strain plot is shown in Figure 3.55. The stress values at zero strain are ±67.5 MPa and the maximum plastic strain range (at zero stress) is ±0.00372.

![Shear stress versus shear strains](image2)

**Figure 3.55: Shear stress versus shear strains shows softening behavior.**
The axial stress versus axial strain plot is shown in Figure 3.56. The axial strain cycles as the axial stress is in cyclic control. The increase in the axial strain is much greater during the axial stress hold at the maximum stress as compared to the hold at the minimum stress.

![Graph showing axial stress versus axial strain with cycle numbers 2 and 200 highlighted.](image)

**Figure 3.56: Axial stress versus axial strain.**

<table>
<thead>
<tr>
<th>Cycle Number</th>
<th>$\varepsilon_{\text{max}}$</th>
<th>$\varepsilon_{\text{min}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.0008398</td>
<td>0.00058</td>
</tr>
<tr>
<td>20</td>
<td>0.004453</td>
<td>0.004148</td>
</tr>
<tr>
<td>200</td>
<td>0.04408</td>
<td>0.04377</td>
</tr>
<tr>
<td>273 (second last)</td>
<td>0.06028</td>
<td>0.0599</td>
</tr>
</tbody>
</table>

**Table 3.11: Axial strain maximum-minimum values over cycle number.**

**Post Test Observation:** The specimen suffered localized deformation in the gage section and its outer diameter changed substantially. This is reported in Table 3.12. The diameter changes were measured over 50 mm of the gage section of the material. The localized deformation of the material is shown in Figure 3.57. The maximum change in the specimen diameter was recorded as 3.34%.
Table 3.12: Change in the outer diameter of the specimen at the end of test 7

<table>
<thead>
<tr>
<th>Position</th>
<th>Outer Diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial gage section diameter = 21 mm</td>
<td></td>
</tr>
<tr>
<td>1 – 19 mm away from center towards top</td>
<td>20.57</td>
</tr>
<tr>
<td>2 – 12.7 mm away from center towards top</td>
<td>20.62</td>
</tr>
<tr>
<td>3 – 6.35 mm away from center towards top</td>
<td>20.3</td>
</tr>
<tr>
<td>4– Center</td>
<td>20.4</td>
</tr>
<tr>
<td>5 – 6.35 mm away from center towards bottom</td>
<td>20.5</td>
</tr>
<tr>
<td>6 – 12.7 mm away from center towards bottom</td>
<td>20.32</td>
</tr>
<tr>
<td>7 – 19 mm away from center towards bottom</td>
<td>20.42</td>
</tr>
</tbody>
</table>

Figure 3.57: Localized deformation in the specimen after the test.
3.2.4 Test 8: MR2, 850°C, 0.04%/s strain rate

Test Parameters and Description: This test was conducted on Specimen 617-10 to show the effect of lower temperature and lower strain rate on material behavior. The testing parameters and the axial stress-shear strain plot are shown in Table 3.13 and Figure 3.58 respectively. This test was interrupted after 10 minutes (18 cycles) as the heater switched off causing the temperature interlocks to stop the test. On further investigation, it was found that the center thermocouple wires had touched the coils causing a short circuit. This tripped the laboratory circuit board fuse for the heater, switching it off. The heater was re-started immediately and ran for another 1950 cycles (19.5 hours) during which the shear stress values decreased cyclically and the angle of twist increased – causing the angle limit detector to interlock and stop the test. The axial strain was close to 4% at this point. The angle of twist of the actuator rotates to create the specified shear strain in the material. The angle of twist increases during the test due to cyclic softening in the material.

Table 3.13: Test parameters for Test 8

<table>
<thead>
<tr>
<th>Test Description</th>
<th>MR2, 850°C, 0.04%/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial Load Amplitude</td>
<td>±254.8 lb (1134 N)</td>
</tr>
<tr>
<td>Constant Axial Load</td>
<td>254.8 lb (1134 N)</td>
</tr>
<tr>
<td>Axial Loading Rate</td>
<td>56.62 lb/s (252 N/s)</td>
</tr>
<tr>
<td>Angle of twist</td>
<td>±0.4320 degrees</td>
</tr>
<tr>
<td>Rate of Angle of twist</td>
<td>0.0960 deg/s</td>
</tr>
<tr>
<td>Cycles to failure</td>
<td>1968 (failure due to crack)</td>
</tr>
<tr>
<td>Time to failure</td>
<td>1181 minutes</td>
</tr>
</tbody>
</table>
Material Behavior: The axial strain versus time and number of cycles plot is shown in Figure 3.59. The rate of increase in axial strain decreases with time. The increase in axial strain is also slower compared to the other MR2 tests. This is expected as the test temperature is lower and the loading rate slower compared to the other tests. The axial strain at the end of the test was approximately 0.041.
The maximum-minimum shear stress shows cyclic hardening for 80 - 90 cycles followed by gradual cyclic softening behavior (Figure 3.60). A large crack formed in the specimen and caused the anomalous rise in shear stress values at the end of the test as the crack growth direction changed. The maximum shear stress is 134 MPa and by the end of the test, the shear stress softens by 90% of the maximum.

![Shear stress versus number of cycles.](image)

**Figure 3.60: Shear stress versus number of cycles.**

The shear stress-strain plot is shown in Figure 3.61. The stress values at zero strain are ±70.8 MPa and the maximum plastic strain range (at zero stress) is 0.00268. There are also some oscillations in the last few cycles of the plot which could have been due to the presence of the large crack in the specimen.
The axial stress versus axial strain plot is shown in Figure 3.62. The increase in axial strain is more when the axial stress is constant at 24 MPa, whereas it is lower when the axial stress is constant at 0 MPa. Variation in the axial strain data is higher at 200 cycles as compared to the second cycle.
Table 3.14: Axial strain maximum-minimum values over cycle number.

<table>
<thead>
<tr>
<th>Cycle Number</th>
<th>$\varepsilon_{\text{max}}$</th>
<th>$\varepsilon_{\text{min}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.0007525</td>
<td>0.000302</td>
</tr>
<tr>
<td>20</td>
<td>0.001764</td>
<td>0.001282</td>
</tr>
<tr>
<td>200</td>
<td>0.006785</td>
<td>0.006316</td>
</tr>
<tr>
<td>1967</td>
<td>0.04169</td>
<td>0.04099</td>
</tr>
</tbody>
</table>

Post test Observation: A large transverse crack formed outside the gage section, 7.6 mm away from top extensometer probe shown in Figure 3.63.

Figure 3.63: Large crack observed at the end of test 8.
3.2.5 Comparison between MR2 tests

**Axial strain versus number of cycles:** The axial strain versus number of cycles and time is shown in Figure 3.64 (a) and (b) for all four MR2 tests. The effect of temperature on axial strain accumulation is clearly observed in the plot. The accumulation of axial strain is greater at 950°C compared to 850°C. The lower loading rate has led to more axial strain accumulation over the same number of cycles for test 3 – 950°C, 0.04%/s as compared to test 1 – 950°C, 0.1%/s. The effect of loading rate at 850°C is relatively small. Axial strain accumulation over time is also greater for test 1 – 950°C, 0.1%/s compared to test 3 – 950°C, 0.04%/s. However, for the 850°C tests, the axial strain accumulation over time is greater for the 0.1%/s test. The rate of axial strain accumulation is almost linear for 950°C tests, whereas the rate of increase continuously decreases for the 850°C tests.
Figure 3.64: Axial strain versus number cycles (a) and time (b) for the four MR2 tests shows the comparison between the axial strain accumulation for different tests.
Shear stress versus number of cycles: The maximum-minimum shear stress versus number of cycles plot for the MR2 tests are shown in Figure 3.65. The effect of temperature on cyclic hardening-softening behavior can be seen from the plot. The maximum-minimum shear stress is much higher for the 850°C tests compared to the 950°C tests. Slower loading rate led to lower shear stress compared to the higher loading rate for both the set of experiments at the two different temperatures, because the viscoplastic deformation had more time to occur.

![Shear stress versus number of cycles](image)

Figure 3.65: Combined plot for shear stress versus number of cycles.
**Shear stress versus shear strain:** The shear stress-shear strain plots for the different tests are shown in Figure 3.66. Only the first and the last hysteresis loops are shown in these plots. The plots indicate the amount of plastic strain that is present in the material at zero stress. These values have been reported before for each test. Comparison between common strain rate tests clearly shows that the maximum plastic strain range (at zero stress) at the higher temperature is greater compared to the lower temperature test. However, effect of loading rate is not clear. The lower loading rate has led to higher plastic strain range (at zero stress) for the 950°C test. However, the loading rate does not seem to have a significant effect at 850°C.
Figure 3.66: Shear stress-shear strain plots for different tests show the amount of plastic strain at zero stress.
3.3 Comparison between MR1 and MR2 tests

1. Test 1 – MR1 and Test 5 – MR2 at 950°C and 0.1%/s: The different comparison plots for test 1 and test 5 are shown below in Figure 3.67-3.69. The axial strain versus number of cycles plot for test 1 and test 5 shows that axial strain accumulation and rate of accumulation is different for the two loading paths. The strain accumulation is higher for the MR2 test over the same number of cycles as compared to the MR1 test. It must be kept in mind that the time period of each cycle is different for the MR1 and MR2 tests. The time period of each cycle for the MR2 tests is almost twice that of the MR1 tests. All the MR1 test plots have been shown in blue and the MR2 plots in red.

![Axial strain versus number of cycles plot](image)

*Figure 3.67: Axial strain versus number of cycles plot for test 1 and test 5 shows the different strain accumulation and rate of accumulation for different loading paths.*

The maximum - minimum shear stress for both the loading paths are similar as shown in Figure 3.68. The rate of cyclic softening is identical for the tests.
Figure 3.68: Shear stress versus number of cycles for test 1 and test 5 show similar levels of maximum and minimum stress.

The plastic strain range (at zero stress) is different for the two tests as shown in Figure 3.69, possibly due to the different strain ranges of testing for the MR1 and MR2 tests. The plastic strain at zero stress is higher for the MR1 test compared to the MR2 test. However, the different strain range of testing does not seem to affect the stress range as it is comparable for both the tests.

Figure 3.69: Shear stress versus shear strain plot for test 1 and test 5 show that the plastic strain at zero stress is different for the both the tests.
2. Comparison between Test 2 – MR1 and Test 6 – MR2 at 850°C and 0.1%/s: The different comparison plots for test 2 and test 6 are shown below in Figures 3.70-3.72. The axial strain versus number of cycles plot for test 2 and test 6 shows that axial strain accumulation and rate of accumulation is different for different loading paths. It is higher for MR2 test as compared to the MR1 test over the same number of cycles.

![Axial strain versus number of cycles plot](image)

Figure 3.70: Axial strain versus number of cycles plot for test 2 and test 6 shows the different strain accumulation and rate of accumulation for different loading paths.

The maximum and minimum shear stress versus number of cycles for different loading path is shown in Figure 3.71. The shear stress range is slightly lower for the MR2 test.
Figure 3.71: Shear stress versus number of cycles for test 2 and test 6 show comparable levels of maximum and minimum stress.

The shear stress versus shear strain plot is shown in Figure 3.72. The plastic strain range (at zero stress) is less for the MR2 test compared to the MR1 test. Also, the stress range for the MR1 test is higher than the stress range for the MR2 tests, which could be due to the higher strain range used for testing in the MR1 tests.

Figure 3.72: Shear stress versus shear strain plot for test 2 and test 6 show that the plastic strain at zero stress is different for the both the tests.
3. **Comparison between Test 3 – MR1 and Test 7 – MR2 at 950°C and 0.04%/s**: The different comparison plots for test 3 and test 7 are shown below in Figures 3.73-3.75. The axial strain versus number of cycles plot for test 3 and test 7 shows significant difference in the rate of axial strain accumulation. The strain accumulation in the MR2 test is much higher as compared to the MR1 test over the same number of cycles.

![Figure 3.73: Axial strain versus number of cycles plot for test 3 and test 7 shows the significant difference in the axial strain accumulation.](image)

The maximum and minimum shear stress versus number of cycles plot for the two tests is shown in Figure 3.74. The stress range is comparable for both the tests.
Figure 3.74: Shear stress versus number of cycles for test 3 and test 7 show similar levels of maximum and minimum stress.

The plastic strain range (at zero stress) is greater for the MR1 test compared to the MR2 test, whereas the stress range is comparable for both the tests as shown in Figure 3.75.

Figure 3.75: Shear stress versus shear strain plot for test 3 and test 7 show that the plastic strain at zero stress is different for the both the tests.
4. Comparison between Test 4 – MR1 and Test 8 – MR2 at 850°C and 0.04%/s: The different comparison plots for test 4 and test 8 are shown below in Figures 3.76-3.78. The axial strain versus number of cycles plot for test 4 and test 8 shows that axial strain accumulation is comparable for both the tests.

![Axial strain versus number of cycles plot for test 4 and test 8](image)

Figure 3.76: Axial strain versus number of cycles plot for test 4 and test 8 shows the different strain accumulation and rate of accumulation for different loading paths.

The maximum and minimum shear stress versus number of cycles plot for the two tests is shown in Figure 3.77. The stress range for the MR2 test is slightly lower than the MR1 test.
Figure 3.77: Shear stress versus number of cycles for test 4 and test 8 show similar levels of maximum and minimum stress.

The shear stress versus shear strain plot is shown in Figure 3.78. The plastic strain range (at zero stress) is less for the MR2 test compared to the MR1 test and the stress range is higher for the MR1 test compared to the stress range for the MR2 tests.

Figure 3.78: Shear stress versus shear strain plot for test 4 and test 8 show that the plastic strain at zero stress is different for the both the tests.
In general the following observations can be made about the MR1 and MR2 comparison plots:

- Axial strain accumulation is similar for the 950°C, 0.1%/s and 850°C, 0.04%/s tests but is significantly different for 850°C, 0.1%/s and 950°C, 0.04%/s tests.
- The shear stress range is comparable for all the tests.

The results for all the MR1 and MR2 tests have been summarized in Table 3.15.

### Table 3.15: Table summarizing the MR1 and MR2 test results.

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Test Name</th>
<th>Test Strain range (rad)</th>
<th>Cycle to failure</th>
<th>Time to failure (min)</th>
<th>Axial strain at failure (m/m)</th>
<th>Maximum shear stress (MPa)</th>
<th>Plastic strain range (rad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>MR1, 950°C, 0.1%/s</td>
<td>0.002</td>
<td>900</td>
<td>120</td>
<td>0.055</td>
<td>111</td>
<td>0.00446</td>
</tr>
<tr>
<td>2</td>
<td>MR1, 850°C, 0.1%/s</td>
<td>0.002</td>
<td>3770</td>
<td>502</td>
<td>0.053</td>
<td>145</td>
<td>0.00317</td>
</tr>
<tr>
<td>3</td>
<td>MR1, 950°C, 0.04%/s</td>
<td>0.002</td>
<td>1300</td>
<td>434</td>
<td>0.130</td>
<td>103</td>
<td>0.00450</td>
</tr>
<tr>
<td>4</td>
<td>MR1, 850°C, 0.04%/s</td>
<td>0.002</td>
<td>3230</td>
<td>1077</td>
<td>0.061</td>
<td>140</td>
<td>0.00346</td>
</tr>
<tr>
<td>5</td>
<td>MR2, 950°C, 0.1%/s</td>
<td>0.0018</td>
<td>568</td>
<td>136</td>
<td>0.038</td>
<td>107</td>
<td>0.00349</td>
</tr>
<tr>
<td>6</td>
<td>MR2, 850°C, 0.1%/s</td>
<td>0.0018</td>
<td>2247</td>
<td>540</td>
<td>0.0515</td>
<td>140</td>
<td>0.00230</td>
</tr>
<tr>
<td>7</td>
<td>MR2, 950°C, 0.04%/s</td>
<td>0.0018</td>
<td>274</td>
<td>164</td>
<td>0.060</td>
<td>99</td>
<td>0.00372</td>
</tr>
<tr>
<td>8</td>
<td>MR2, 850°C, 0.04%/s</td>
<td>0.0018</td>
<td>1968</td>
<td>1181</td>
<td>0.041</td>
<td>134</td>
<td>0.00268</td>
</tr>
</tbody>
</table>

Note: This failure is based on the time after which the test was stopped due to crack growth or excessive deformation in the specimen. A clear failure criterion could not be defined for these tests nor should this data be used for predicting ultimate life of the material.
Chapter 4

Conclusion and Future Work

4.1 Conclusion

The mechanical behavior of Inconel 617 was investigated through axial-torsion experiments. These experiments can be time consuming and challenging to setup. A detailed procedure list for testing was developed and safe working conditions for experimentation were established. The effect of temperature (950°C, 850°C) and loading rate (0.1%/s, 0.04%/s) on the mechanical behavior of the material has been investigated. Two loading paths were followed that promote axial strain ratcheting. The technologically significant conclusions are summarized below:

1. **Temperature:** Axial strain accumulation for the same number of cycles, caused by creep and ratcheting, is significantly greater at 950°C compared to 850°C for both the MR1 and MR2 tests. The maximum-minimum shear stress plots show cyclic softening behavior at 950°C whereas at 850°C, the material cyclically hardens for the initial cycles and then gradually softens. The stress range is also much larger at 850°C (approximately 140 MPa) compared to the 950°C tests (approximately 100 MPa) for both the loading paths. The shear stress versus shear strain plots show that the amount of plastic strain (at zero stress) at 950°C is between 1.3 - 1.5 times the amount at 850°C for both MR1 and MR2 tests. Specimens tested at 850°C had longer time to failure compared to the 950°C tests. The rate of axial strain accumulation for test 7 (MR2, 950°C, 0.04%/s) was much larger compared to all the other tests.
2. **Loading rate:** The effect of loading rate on the axial strain accumulation was clearer for the MR1 tests compared to the MR2 tests. Slower loading rate led to more axial strain ratcheting for the MR1 tests for the same number of cycles. However, the effect of loading rate on the axial strain accumulation cannot be clearly characterized for the MR2 tests. Lower loading rate also led to slightly lower maximum-minimum shear stress as compared to the higher loading rate. This is clear in all the MR1 and MR2 plots. The effect of loading rate on the plastic strain range (at zero shear stress) could not be clearly characterized.

3. **Failure:** The failure mode for the tests, except the 950°C, 0.04%/s, was through crack propagation and growth. Large lateral or angular cracks were observed in the MR1 tests, whereas the cracks in the MR2 test were all laterally oriented. All MR2 cracks were observed at approximately the same spot – 7.6 mm away from the indent for the top extensometer probe, outside the gage section. The specimens in the 950°C, 0.04%/s MR1 and MR2 tests experienced excessive deformation rather than crack growth.

Comparisons have also been made for MR1 and MR2 tests for the same temperature and loading rate. These comparisons show differences in strain accumulation and cyclic hardening-softening behavior that have been discussed in the previous chapter. Photographs of the failed specimens indicate that failure have resulted from crack growth as well as excessive deformation. The behavior of Inconel 617 at elevated temperatures will depend on a number of different phenomena. Creep, fatigue and ratcheting will all contribute towards strain accumulation, crack growth and ultimate life of the specimen.
4.2 Future Work

This work represents the first part of the axial-torsion test program, replicate tests and other loading cases will be conducted to gain a deeper understanding of the material behavior. Microstructural and fractographic investigation of the failed specimens will be undertaken to understand the crack initiation and growth. Additionally, tests with a higher degree of non-proportional loadings can be carried out and strain controlled tests can also be used to study the relaxation behavior of the material. Another possibility is to conduct tests with a higher strain range and explore the effect of strain range on the material behavior. Creep test should also be conducted to quantify the amount of creep strain in the axial strain accumulation. Constitutive models built with the help of this data can be used to predict the ultimate life of Inconel 617 in various high temperature applications. Comparison between modeling and experimental data would help in building more robust models. Robust models can predict the ultimate life of nuclear and power plant components with greater certainty and improve efficiency, saving costs and providing a better future for all.
Bibliography

1. Inconel alloy 617, Publication Number SMC-029, Special Metals Corporation, 2005.


37. Research and Development Status, INL/EXT-10-19259, August 2010

Appendix

The MATLAB code for calculating the stresses, strain and for making the plots is attached below. Also, note that sections of the code are commented and used only selectively.

```matlab
% --------------Data Analysis for load data on Inconel specimen-------------%
% -----------------------Program by MAINAK SENGUPTA---------------------%
%----------------------------Specimen No 7-----------------------------%
%----------------------Data Acquired at 10 points every second----------%

clear all;

%----------------------------Variable Assignment and reading through loops-----%
OD = 0.824867;  
ID = 0.703933;  
A = (3.14159/4)*(OD^2-ID^2);

%-----Upper and lower bounds of the xls data file is min and max--------%
LL=input('Input the value of Lower Limit (minimum 5): ');
UL=input('Input the value of Upper Limit (maximum xls file row-1): ');

spec1 = csvread('csvlist.csv',LL,0,[LL 0 UL 7]);
n = UL-LL; %actual Note - not considering 5 data points for average loop to run
cycletime = 14.4;

for i = 1:n
    axialforce(i)=spec1(i,2);axialstrain(i)=spec1(i,3);
sheartorque(i)=spec1(i,5);shearstrain(i)=spec1(i,6);time(i)=spec1(i,7);shearangle(i)=spec1(i,4);temperature(i)=spec1(i,8);
end

%---------------------Calculating the Cycle Number----------------------%
for k=1:n
    cycleno(k)=floor(time(k)/(20*0.99870356));
end

%---------------------Averaging the Load data--------------------------%
for l=1:10:n-9
    Axialavg(l)=(axialforce(l)+axialforce(l+1)+axialforce(l+2)+axialforce(l+3)+axialforce(l+4)+axialforce(l+5)+axialforce(l+6)+axialforce(l+7)+axialforce(l+8)+axialforce(l+9))/10;
end
```
%---------------------Calculating the Stress and Strain---------------------%
for j=1:n
    shearstress(j) = (sheartorque(j)*(OD/2))/((3.14159/2)*((OD/2)^4-(ID/2)^4))*0.006895;
    axialstress(j) = (axialforce(j)/A)*0.006895;
    shearstrainR(j) = ((shearstrain(j)*(OD/2)*3.14159)/180;
    equistress(j) = (((axialstress(j))^2+(shearstress(j)*((3)^0.5))^2))^0.5);
    equistrain(j) = (((axialstrain(j))^2+(shearstrainR(j)/((3)^0.5))^2))^0.5);
end

%-----Calculating the cycles at which specimen failed-------------------%
%-----Based on 90% of the maximum shear stress principle----------------

%maxtorque = shearstress(5);
%counter = 0;
%for j = 1:n
%    if (shearstress(j) > maxtorque)
%        maxtorque = shearstress(j);
%    end
%    cycle = time(j)/(cycletime);
%
%if (counter == 0)
%    if (cycle >= 730)
%        if (shearstress(j) <= 0.9*maxtorque)
%            cycle = maxtorque = shearstress(j);
%        end
%    end
%end
%end

%cycles = time(128960)/8

%---------------------Calculate the peak and valley shear stress------------%
% [maxtab, mintab] = peakdet(axialstrain, 0.00005);
% [maxtab, mintab] = peakdet(shearstress, 5);

%plot(mintab(:,1), mintab(:,2), 'r*');
n1=length(maxtab)-1;
for i1=1:n1
    cyclenumber(i1)=i1;
    meanSstress(i1)=(maxtab(n1,2)+mintab(n1,2))/2;
end

%hold on; plot(cyclenumber, maxtab(:,2), 'b*'); hold on;
%hold on; plot(cyclenumber, meanSstress, 'b*'); hold on;

%----------------------------------------Averaging the Axial Strain data----------------------------------------%
for l=1:10:n-9
    Axialstrainavg(l)=(axialstrain(l)+axialstrain(l+1)+axialstrain(l+2)+axialstrain(l+3)+axialstrain(l+4)+axialstrain(l+5)....
    +axialstrain(l+6)+axialstrain(l+7)+axialstrain(l+8)+axialstrain(l+9))/10;
    for g=l+1:l+9
        Axialstrainavg(g)=Axialstrainavg(l);
    end
end

% --------------------------------Calculate E and G---------------------------------------%
%G = 5032.5*(((OD/2)*((3.14159/2)*((OD/2)^4-(ID/2)^4)))/(3.14159)/180)
%G1 = (shearstress(154)-shearstress(73))/(shearstrainR(154)-shearstrainR(73))
%E = 3.5360E+06/A
%E1= (axialstress(30)-axialstress(2))/(axialstrain(30)-axialstrain(2))

%------------------------------------------Plotting------------------------------------------%

%1: plot(time,axialstress,time,shearstress);legend('Axialstress','Shearstress');xlabel('Time (Seconds)');
     ylabel('Stress (MPa)');
%2: plot(time,axialstrain,time,shearstrainR);legend('Axialstrain','Shearstrain');xlabel('Time (Seconds)');
     ylabel('Strain');
%3: plot(axialstrain,axialstress);xlabel('Axial Strain');ylabel('Axial Stress (MPa)');
%4: plot(shearstrainR,shearstress);xlabel('Shear Strain');ylabel('Shear Stress (MPa)');
%5: plot(axialstrain,axialstress);xlabel('Axial Strain');ylabel('Shear Stress (MPa)');
%6: plot(shearstrainR,axialstrain);xlabel('Shear Strain (%)');ylabel('Axial Stress (MPa)');
%7: plot(shearstrainR,axialstrain);xlabel('Shear Strain (%)');ylabel('Axial Stress (MPa)');
%8: plot(shearstrainR,axialstrain);xlabel('Shear Strain (%)');ylabel('Axial Stress (MPa)');
%9: plot(cycleno,shearstress);xlabel('Cycle Numbers');ylabel('Shear Stress (MPa)');
%10: plot(cycleno,Axialavg);xlabel('Cycle Numbers');ylabel('Average Axial Force (Lb)');
%11: plot(time(1:165:990),axialstrain(1:165:990));legend('Axialstrain');ylabel('Strain');xlabel('Time (Seconds)');

%hold on; plot(x1((n-1)*144+1:(n)*144+1),y1((n-1)*144+1:(n)*144+1));

MATLAB code for calculating the maximum-minimum shear stress versus number of cycles is attached below.

function [maxtab, mintab]=peakdet(v, delta, x)
%PEAKDET Detect peaks in a vector
% [MAXTAB, MINTAB] = PEAKDET(V, DELTA) finds the local
% maxima and minima ("peaks") in the vector V.
% MAXTAB and MINTAB consists of two columns. Column 1
% contains indices in V, and column 2 the found values.
%
% With [MAXTAB, MINTAB] = PEAKDET(V, DELTA, X) the indices
% in MAXTAB and MINTAB are replaced with the corresponding
% X-values.
%
% A point is considered a maximum peak if it has the maximal
% value, and was preceded (to the left) by a value lower by
% DELTA.
%
% Mainak Sengupta
maxtab = [];
mintab = [];
v = v(:); % Just in case this wasn't a proper vector

if nargin < 3
    x = (1:length(v))';
else
    x = x(:);
    if length(v)~= length(x)
        error('Input vectors v and x must have same length');
    end
end

if (length(delta(:)))>1
    error('Input argument DELTA must be a scalar');
end
if delta <= 0
    error('Input argument DELTA must be positive');
end

mn = Inf; mx = -Inf;
mnpos = NaN; mxpos = NaN;

lookformax = 1;

for i=1:length(v)
    this = v(i);
    if this > mx, mx = this; mxpos = x(i); end
    if this < mn, mn = this; mnpos = x(i); end

    if lookformax
        if this < mx-delta
            maxtab = [maxtab ; mxpos mx];
            mn = this; mnpos = x(i);
            lookformax = 0;
        end
    else
        if this > mn+delta
            mintab = [mintab ; mnpos mn];
            mx = this; mxpos = x(i);
            lookformax = 1;
        end
    end
end

This MATLAB code is used for making combined plots.

% This code is selectively used for picking up data from plots and making
% combined plots.

m=figure;hold on
% %for i=1:4
% fig=open('1.fig');
% c=get(gca)
% f=get(c.Children)
% x1=f.XData;
% y1=f.YData;
% figure(m)
% plot(dataX,dataY)
%end
%

fig=open('4.fig');
c2=get(gca)
f2=get(c2.Children)
x1=f2.XData;
y1=f2.YData;
ax1 = gca;
set(ax1,'XColor','k','YColor','k')
hl1 = line(x1,y1,'Color','k');

% ax2 = axes('Position',get(ax1,'Position'),...
% 'XAxisLocation','top','YAxisLocation','right',...
% 'Color','none',...
% 'XColor','k','YColor','k');
%
% fig=open('Axial StrainC.fig');
% c1=get(gca)
% f1=get(c1.Children)
% x2=f1.XData;
% y2=f1.YData;
%
% hl2 = line(x2,y2,'Color','k','Parent',ax2);
Sample Test template on MPT:
FlexTest 40 Screen shot showing the different interlock values and scopes: