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A Simplified Approach to Thermomechanical Fatigue and Application to V-shaped Notches

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A SIMPLIFIED APPROACH TO THERMOMECHANICAL FATIGUE AND APPLICATION TO V-SHAPED NOTCHES

by

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Abstract

A vast array of high value parts in land- and air-based turbomachinery are subjected to non-isothermal cycling in the presence of mechanical loading. Crack initiation, growth and eventual failure more significantly reduce life in these components compared to isothermal conditions. More accurate simulation of the stress and strain evolution at critical locations of components, as well as test specimens, can lead to a more accurate prediction of remaining life to a structural integrity specialists. The focus of this thesis is to characterize the effects of thermomechanical fatigue (TMF) on generic turbomachinery alloy. An expression that can be used to estimate the maximum and minimum stress under a variety of loading conditions is formulated. Analytical expressions developed here are modifications of classic mechanics of materials methods (e.g. Neuber's Rule and Ramberg-Osgood). The novel models are developed from a collection of data based on parametric finite element analysis to encompass the complex load history present in turbine service conditions. Relevance of the observations and formulated solutions are also explored for the case of a tensile specimen containing a v-shaped notch. Accurate estimations of non-isothermal fatigue presented here endeavor to improve component lifing and decrease maintenance costs.

To my parents and my brother

Acknowledgements

I would like to extend my deepest thanks to Dr. Ali P. Gordon, who has been a critical asset in the completion of this thesis. Dr. Gordon has been both advisor and instructor throughout the project. I am grateful for the opportunities that he has presented and the knowledge he has shared. I would also like to thank Steven Kraft, Scott Keller, Justin Karl, Charles Mansfield, Nathan Mutter and other members of the Mechanics of Materials Research Group. Their experience and resourcefulness has been tremendous help. My gratitude also goes to Siemens and the Work Force of Central Florida, who have provided funding for this project.

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Variable

δ	Displacement [mm]
$\dot{\varepsilon}$	Strain Rate [mm/mm/s]
$\dot{\varepsilon}_{creep}$	Creep Strain Rate [mm/mm/s]
$\dot{\varepsilon}_{el}$	Elastic Strain Rate [mm/mm/s]
ε	Local Strain [mm/mm]
ε_{creep}	Creep Strain [mm/mm]
ε_{el}	Elastic Strain [mm/mm]
ε_{in}	Inelastic Strain [mm/mm]
ε_{max}	Maximum Strain [mm/mm]
ε_{min}	Minimum Strain [mm/mm]
ε_{pl}	Plastic Strain [mm/mm]
ε_{tot}	Total Strain [mm/mm]
$\Delta\varepsilon$	Local Strain Range [mm/mm]
$\Delta\varepsilon_{iso,max}$	Local Strain Range for the Isothermal Response at the Maximum Temperature [mm/mm]
$\Delta\varepsilon_{TMF}$	Local Strain Range for the TMF Response [mm/mm]
φ	Phase Angle [°]
$\dot{\sigma}$	Stress Rate [MPa/s]
σ	Local Stress [MPa]
σ_m	Mean Stress [MPa]

σ_{max}	Maximum Stress [MPa]
σ_{min}	Minimum Stress [MPa]
σ_{relax}	Total Accumulated Stress Relaxation [MPa]
σ_{UTS}	Ultimate Tensile Strength [MPa]
σ_y	Yield Stress [MPa]
$\Delta\sigma$	Local Stress Range [MPa]
$\Delta\sigma_{iso,max}$	Local Stress Range for the Isothermal Response at the Maximum Temperature [MPa]
$\Delta\sigma_{TMF}$	Local Stress Range for the TMF Response [MPa]
θ	Grain Orientation Angle [°]
A	Creep Constant [Norton Power Law]
B	Homologous Modulus [GPa/GPa]
E	Elastic Modulus [MPa]
$E_{iso,max}$	Elastic Modulus at Maximum Isothermal Temperature [GPa]
$E_{iso,min}$	Elastic Modulus at Minimum Isothermal Temperature [GPa]
e_n	Nominal Strain [mm/mm]
K_ε	Effective Strain Concentration Factor [mm/mm]
K_σ	Effective Stress Concentration Factor [MPa/MPa]
K_t	Theoretical Stress Concentration Factor [MPa/MPa]
K'	Cyclic Plastic Modulus [Ramberg-Osgood Relationship]
K^*	Modified Cyclic Plastic Modulus [Modified Ramberg-Osgood Relationship]
K^{**}	Modified Relaxed Cyclic Plastic Modulus [Modified Ramberg-Osgood Relationship]

n	Creep Constant [Norton Power Law]
n'	Cyclic Strain Hardening Exponent [Ramberg-Osgood Relationship]
$n*$	Modified Strain Hardening Exponent [Modified Ramberg-Osgood Relationship]
R	Strain Ratio [mm/mm]
S_n	Nominal Stress [MPa]
ΔS_n	Nominal Stress Range [MPa]
$\Delta S_{n,iso,max}$	Nominal Stress Range for the Isothermal Response at the Maximum Temperature [MPa]
$\Delta S_{n,TMF}$	Nominal Stress Range for the TMF Response [MPa]
t_{hold}	Dwell Time [hr]
T_{max}	Maximum Temperature [°C]
T_{min}	Minimum Temperature [°C]
X	Global x-axis
Y	Global y-axis

Acronyms

ASTM	American Society for Testing and Materials
DS	Directionally-solidified
IP	In-Phase
L	Longitudinal
OP	Out-of-Phase
T	Transverse
TMF	Thermomechanical Fatigue

1. Introduction

The complex service history of a turbine engine subjects critical locations of blades, vanes, and other components to thermomechanical fatigue (TMF), which drastically reduces its life and increases the risk of crack propagation and failure. These components often develop cracks at holes, edges, corners, and hot spots. For computational efficiency, many components are simulated under the assumption of elasticity, and the extent of any localized plasticity is determined analytically. The relationship between remote loading and local stress and strain is yet to be analytically modeled under non-isothermal conditions. Research is needed to extend non-local approaches to conditions that approximate TMF service loading. As a consequence of the models introduced in this study, the usage and maintenance cost of turbomachinery can be reduced without sacrificing safety of the turbine and those who use it.

The conditions necessary to explore the relationship between remote and local stress and strain of a notched specimen under TMF loading will be performed using a variety of temperature profiles, load history, and specimen types. Each of these numerically simulated cases will utilize the standard American Society for Testing and Materials (ASTM) specimens and follow protocols within the ASTM standard E2368 for TMF testing under strain-control to ensure that the results can be synchronized with physical experiments [ASTM Standard E2368, 2005]. The candidate material chosen for this study is a generic directionally-solidified (DS), Ni-base superalloy, as it is one of many materials used in hot gas path components. Those DS materials have increased resistance to fatigue and creep in the longitudinal orientation.

Loading conditions employed in this study bear strong resemblance to service conditions. Simulated material will be cycled from 100°C to peak temperatures of 750°C, 850°C, and

950°C. The material model for the DS superalloy contains properties in the longitudinal (L) and transverse directions (T), though the stresses and strains gathered for each orientation is taken with reference to the loading direction. This provides an accurate assessment of critical conditions in each notched and un-notched specimen.

This thesis continues with a review of recent literature relevant to this study (Chapter 2). Chapter 3 contains information on the candidate material and orientation-dependence of the mechanical properties. Afterwards, an overview of the finite element models and a list of test conditions to which they are applied are discussed in Chapter 4. A step-by-step analysis of un-notched TMF results and associated observations and formulations are covered in Chapter 5, and unified in Chapter 6. Results of non-isothermal notched simulations and discussion on the applicability of isothermal approaches are presented in Chapter 7. Concluding remarks and topics of future study can be found in Chapter 8 and Chapter 9, respectively.

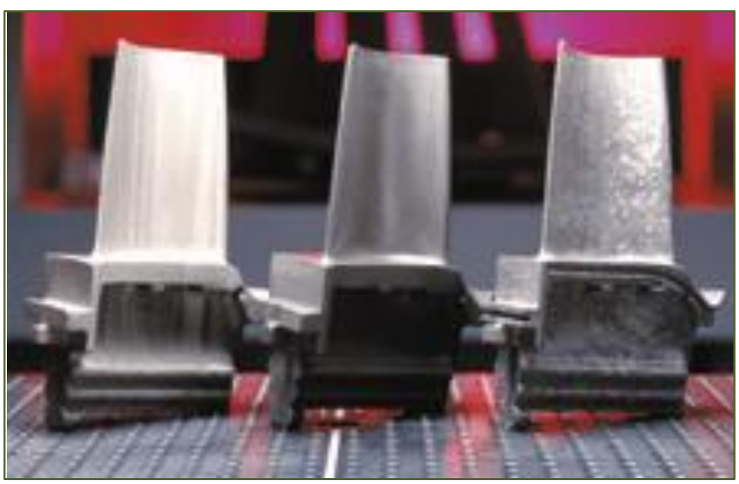


Figure 1.1: Turbine blades created from (left to right) directionally-solidified , single crystal, and polycrystalline materials. [Mechanical Engineering Magazine, 2003]

2. Background

2.1 Neuber's Rule

A stress concentration is the consequence of a geometric discontinuity in a structure, which causes the local stress at the location of this discontinuity to be higher than the average (or nominal) stress of the entire body [Collins, 1993]. Several analytical approaches have been developed to predict the notch root stress and strain based on the elastic or theoretical stress concentration factor, K_t, nominal stress, and material behavior. The most basic of these relationships is Neuber's rule[Neuber, 1961], which is the underlying principle used to compare the stress at a notch tip with the remotely applied load. Neuber’s rule states that

$$K_t^2 = K_\sigma K_\varepsilon = \frac{\sigma}{S_n}\frac{\varepsilon}{e_n} \quad [2.1]$$

where K_σ is the effective stress concentration factor and K_ε is the effective strain concentration factor. The local elastic-plastic stress and strain at the notch tip are represented by σ and ε, respectively. Here, S_n is the nominal (or pseudo) stress and e_n is the nominal (or pseudo) strain present in a remote location, such as a specimen gage length in a notched tensile test.

Typically, the material response at the remote location is assumed to remain elastic during the application of the load, creating localized yielding at the notch tip. Using this so called small-scale yielding assumption, Equation [2.1] can be simplified with the assumption that the material behavior in the area surrounding the notch is dominantly elastic. Alternatively, the yield zone is comparatively small and

$$S_n = Ee_n \quad [2.2]$$

where E, the elastic modulus of the material, to form

$$\frac{K_t^2 S_n^2}{E} = \sigma\varepsilon \qquad [2.3]$$

The left-hand side represents the remote or nominal condition, while the right-hand side gives the local notch tip response. Because the material response relating stress to strain is non-linear, iterative schemes must be used to decouple σ and ε. It should be noted that the total strain, ε, is expressed as

$$\varepsilon = \varepsilon_{el} + \varepsilon_{pl} \qquad [2.4]$$

Where ε_{pl} is the plastic strain and ε_{el} is the elastic strain. Using elastic conditions at a location sufficiently far away from the notch and a hyperbola representing Neuber's rule, the local stress and stain at the notch can be graphically explained as the intersection of the hyperbola and the elastic-plastic stress-strain curve. Figure 2.1 depicts the nominal and local response, and Neuber's hyperbola is shown in Figure 2.2.

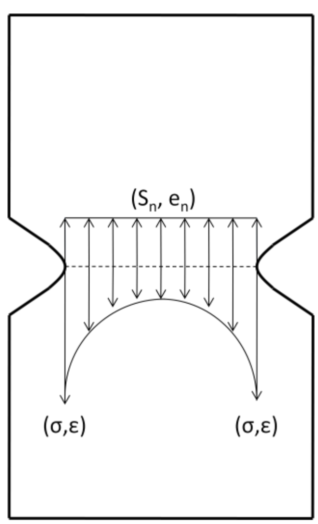


Figure 2.1: Location of Nominal Stress, Nominal Strain, Local Stress, and Local Strain on a Notched Specimen

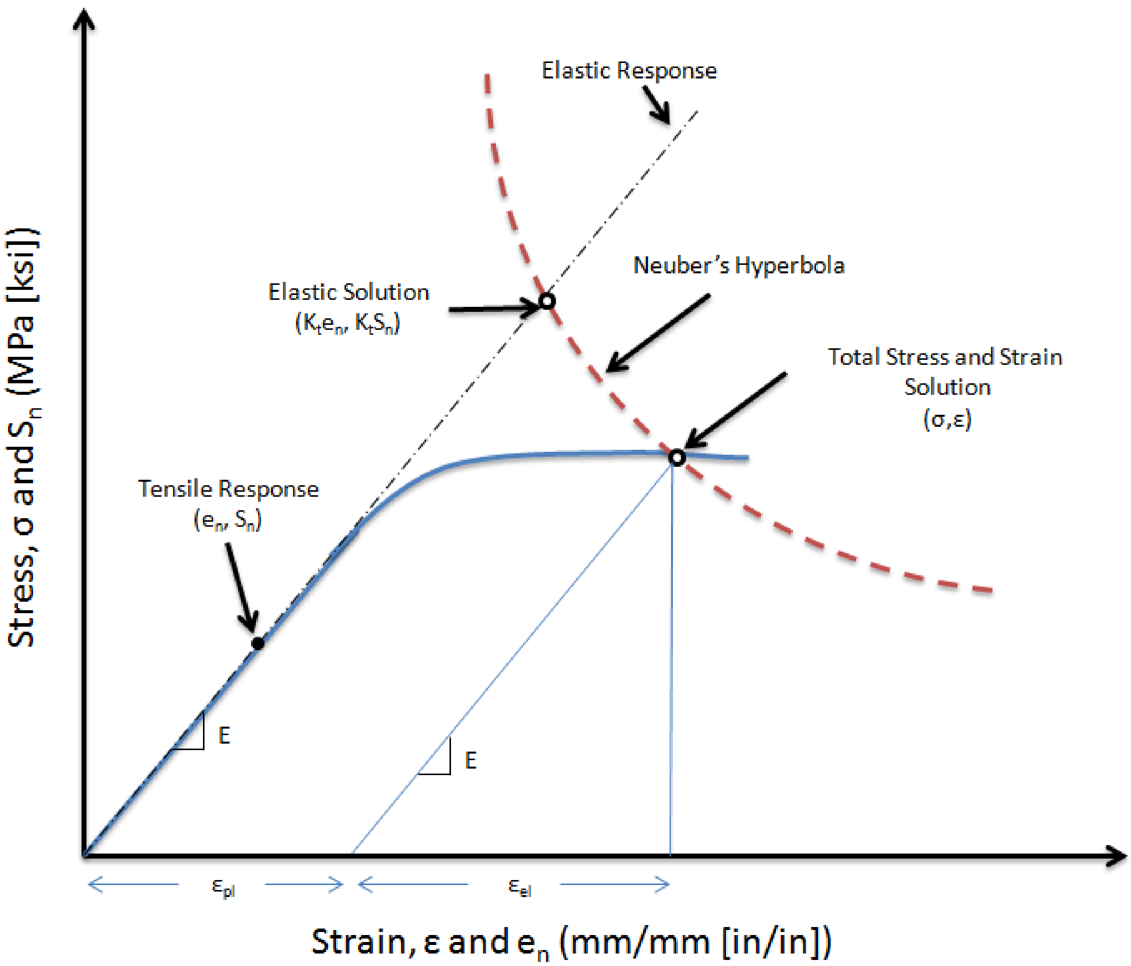


Figure 2.2: Graphical Interpretation of Neuber's Hyperbola Under Isothermal Conditions

This relationship was further developed for use in fatigue loading [Topper, et al., 1969], into

$$(K_t \Delta S_n)^2 = E \Delta\sigma \Delta\varepsilon \qquad [2.5]$$

where ΔS_n is the nominal stress range at the remote location, $\Delta\sigma$ is the local stress range at the notch tip, and $\Delta\varepsilon$ is the local strain range at the notch tip. Equation [2.5] can be expanded by introducing the Ramberg-Osgood equation

$$\Delta\varepsilon = \Delta\varepsilon_{el} + \Delta\varepsilon_{pl} = \frac{\Delta\sigma}{E} + \left(\frac{\Delta\sigma}{K'}\right)^{\frac{1}{n'}} \qquad [2.6]$$

where $\Delta\varepsilon$ is the elastic-plastic strain range, $\Delta\varepsilon_e$ is the elastic strain range, $\Delta\varepsilon_p$ is the plastic strain range, $\Delta\sigma$ is the stress range, n' is the cyclic strain hardening coefficient and K' is the plastic modulus. This forms the local and remote stress relationship

$$\frac{K_t^2 \Delta S_n^2}{2E} = \frac{\Delta\sigma\Delta\varepsilon}{2} = \frac{\Delta\sigma}{2}\left[\frac{\Delta\sigma}{E} + \left(\frac{\Delta\sigma}{K'}\right)^{\frac{1}{n'}}\right] \qquad [2.7]$$

Other modifications have also been proposed, including the Molski-Glinka Approach [Molski, 1981], which uses the strain energy density to form the function

$$\frac{K_t^2 \Delta S_n^2}{2E} = \frac{\Delta\sigma^2}{2E} + \frac{\Delta\sigma}{n'+1}\left(\frac{\Delta\sigma}{K'}\right)^{\frac{1}{n'}} \qquad [2.8]$$

as well as other stress shakedown methods.

The limitation of the documented approaches formulated in Equations [2.1]-[2.8] is that each method assumes isothermal or nearly isothermal conditions. For temperature ranges where E, K', and n' are temperature dependent, these models are not applicable. This can be demonstrated using the graphical approach to Neuber's rule in Figure 2.3. Applying the same hyperbola to the tensile response of two different temperatures yields dissimilar results, making estimation impossible. Neuber's rule has also been extended to creep analysis. Given the non-isothermal nature of TMF this model cannot be directly applied. The objective of this study is to develop analytical approaches to make up for these limitations.

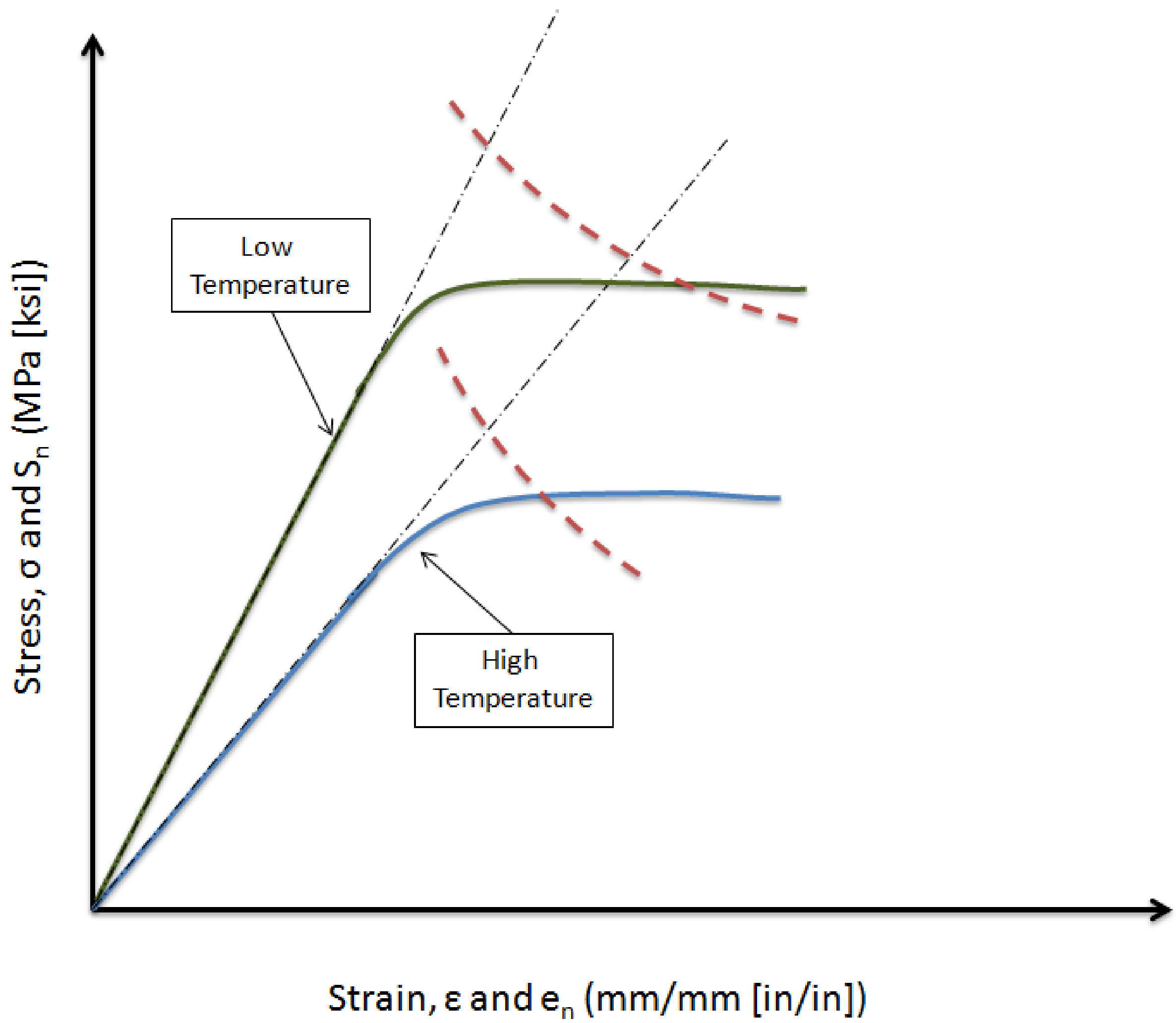


Figure 2.3: Comparison of Low Temperature and High Temperature Isothermal Response Using Neuber's Rule

2.2 Thermomechanical Fatigue

By definition, thermomechanical fatigue is the combination of a thermal cyclic load with a mechanical cyclic load. Similar to low-cycle fatigue (LCF), TMF encompasses a near-unlimited range of load conditions and cycle histories. These variations have unique effects on the mechanical response of the structure, and in many cases lead to permanent damage of the material. In turbine design, TMF is a critical focus of study, as the cycle can be tailored to closely resemble service conditions. TMF is generally applied to a critical location of a component. This would include a start-up period, a working period, a shutdown period, and a rest period.

During start-up, the turbine is activated and the temperature increases as the blades speed up. This translates to a steady increase in temperature stress, and strain on the components. Some creep may be present at the later stages. In the working period, the turbine is fully activated and is fulfilling its function. In this part of the cycle, the thermal and mechanical loads are held constant at peak levels over an extended period of time, which subjects the parts to creep strain, as well as mechanical stresses and strains. Some amount of stress-relaxation and plasticity will also occur. Higher temperatures are desired in this part of the cycle, as the turbine would be more efficient during its period of use; however, a higher temperature would mean an increase in creep, and a decrease in yield strength, which would decrease the lifespan of the turbine.

The shutdown period is the inverse of the start-up period, where the turbine gradually cools down as the mechanical and thermal loads are released. The rest period is generally omitted from turbine TMF models, as it is the hold at the lower temperature when the turbine is off and no loads are present. No creep or load deformation is present during this period. This

TMF cycle can be repeated hundreds or thousands of times until the accumulated damage eventually causes a crack to initiate.

The combination of these loads can occur in-phase or out-of-phase. If the loading is in-phase (IP), the mechanical strain reaches a maximum value at the same time the temperature reaches its peak during each cycle. If the loading is out-of-phase (IP), the maximum mechanical strain is reached when the temperature is at a minimum. True service conditions may vary in hold times, temperatures, and applied load or deformation between cycles. The waveforms for IP and OP loads (shown in Figure 2.4) used in this study are an idealized version of a component service condition that provide an approximation to the effect of TMF assuming that each cycle is identical. These cycles assume a strain-controlled test, and therefore the maximum load may not coincide with the maximum temperature.

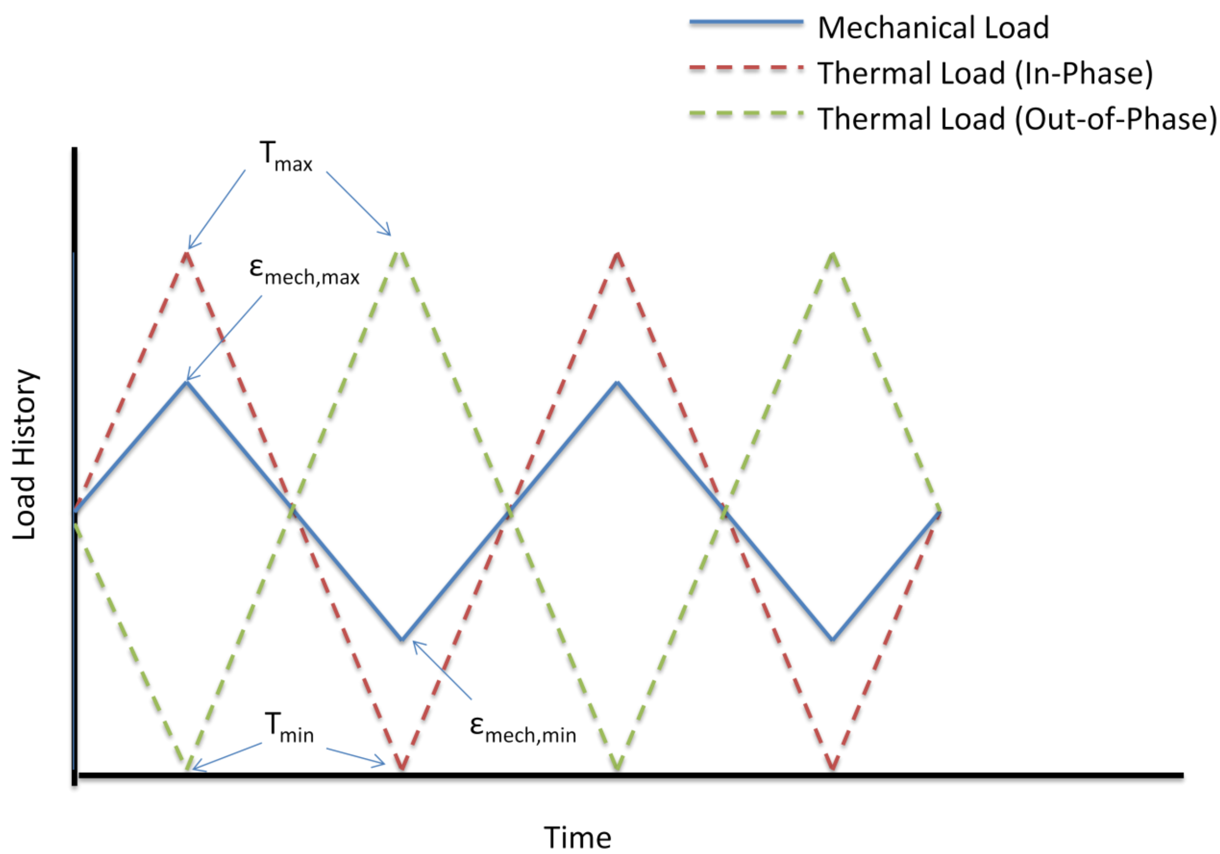


Figure 2.4: Typical Strain-Controlled TMF with In-Phase and Out-of-Phase Loadings

In beam theory, as well as many other engineering applications, two separate loads can be modeled and resolved independently and combined using the principle of superposition. This simplification is not possible in TMF. The elastic modulus, shear modulus, yield strength, and nearly every other mechanical property are a function of temperature, which is constantly changing.

Typical stress-strain responses to isothermal and TMF conditions during a single-cycle strain-controlled completely-reversible tests with a hold time are plotted as hysteresis loops in Figure 2.5. These plots show a definitive difference in material response to isothermal and TMF, as well as IP and OP conditions. Although the strain range, $\Delta\varepsilon$, is the same due to the control method, the stress range $\Delta\sigma$, is different. The strain range is defined as

$$\Delta\varepsilon = \varepsilon_{\max} - \varepsilon_{\min} \qquad [2.9]$$

where ε_{max} is the maximum strain and ε_{min} is the minimum strain in the cycle. Stress range is defined as

$$\Delta\sigma = \sigma_{\max} - \sigma_{\min} \qquad [2.10]$$

where σ_{max} is the maximum stress and σ_{min} is the minimum stress in the cycle. The mean stress σ_m and inelastic strain ε_{in} also depend on the loading condition. The mean stress is the average of the maximum and minimum stress, modeled as

$$\sigma_m = \frac{\sigma_{\max} - \sigma_{\min}}{2} \qquad [2.11]$$

The inelastic strain is the combination of the plastic strain ε_{pl} and the creep strain ε_{creep}, which is equivalent to

$$\varepsilon_{in} = \varepsilon_{pl} + \varepsilon_{creep} = \varepsilon_{tot} - \varepsilon_{el} \qquad [2.12]$$

where ε_{tot} is the total strain and ε_{el} is the elastic strain.

The behavior of tested samples would also be affected by accumulated damage from the mechanical and thermal load history. This means that the loads are not independent. The onset of plasticity and creep, two non-linear deformation modes, would also deny the use of superposition. Thus, TMF must be modeled in such a way that the loads occur simultaneously. Attempts to model the thermal and mechanical loads separately would produce results that differ in terms of life, damage accumulation, and the microstructure itself [ASTM Standard E2368, 2005].

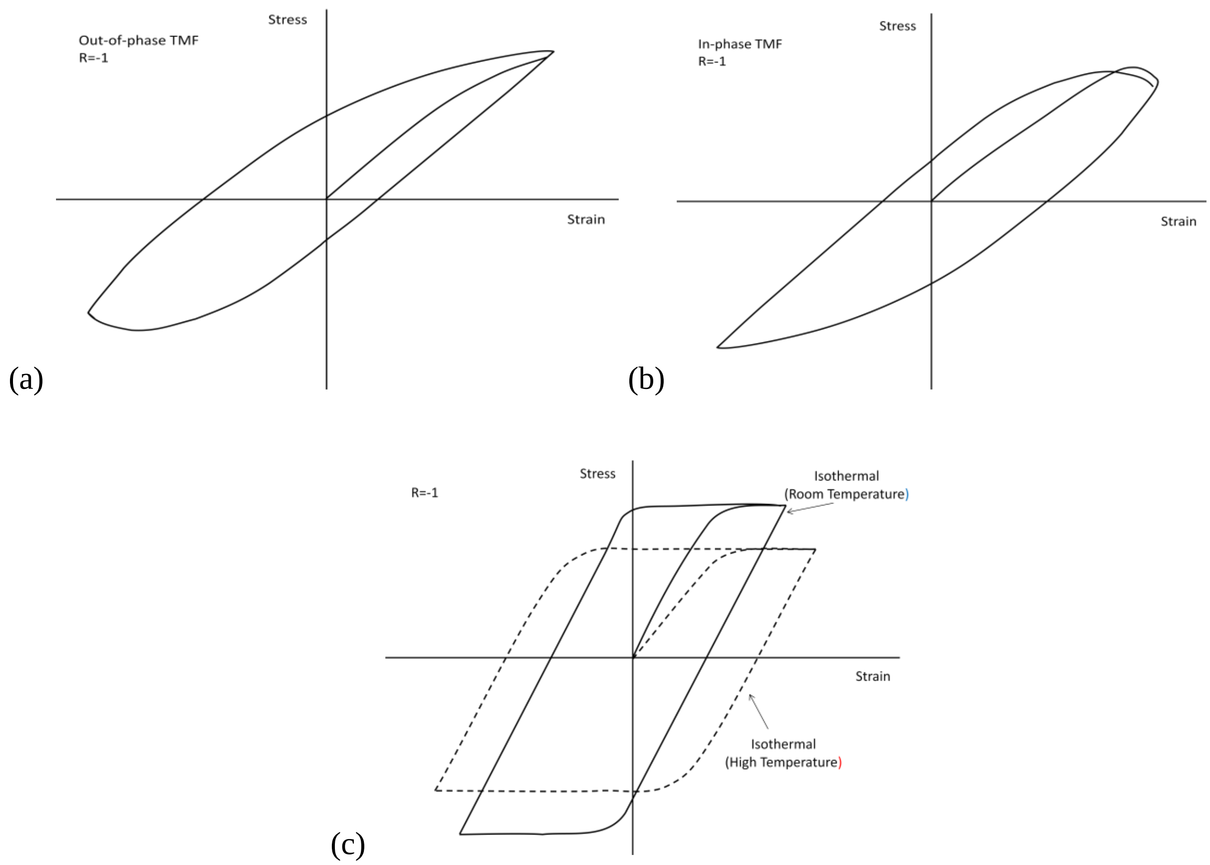


Figure 2.5: Sketch of an (a) Out-of-phase TMF, (b) In-phase TMF, and (c) Isothermal Hysteresis Loop

2.3 Overview of Approach

Previous research shows that the local stresses in a notched TMF loading is bound by the analytic solution to Neuber's rule for the peak and valley isothermal LCF loads [Gordon, et al., 2008]. This suggests that a modification to Neuber's rule can be formulized to provide more accurate estimates; however, more analysis needs to be done.

A better understanding of the effects of TMF in notched structures would allow for more accurate predictions of resulting stresses and lifing models. With these, turbines can be designed to operate at higher temperatures and speeds, boosting performance and efficiency. Accurate TMF models would also reduce maintenance costs where spot inspections can be utilized from finite element models. Improved prediction methods would also curtail extensive combinations of test parameters in TMF material testing.

The overall goal of this study is to develop an approach to estimate TMF response in a V-notch specimen. To do this, a correlation must first be to be found to bridge the gap between isothermal response and the TMF response. This is done using a high-volume parametric series of single-element FE models carried out under a variety of strain ranges, temperatures, and phasing. Once this correlation is formulated into a useable analytical model, creep can be introduced, resulting in an effective TMF approximation method. The correlation can then be used as modification to traditional shakedown methods to determine the response at a notch tip using a remote stress and strain using a multi-element FE model of a notched test specimen.

3. Material Modeling

Blades, vanes, and other components of gas turbine engines are routinely subjected to large amounts of heat and load along a known axis. To improve creep resistance and other mechanical properties along this axis, directionally-solidified materials can be used. Directionally-solidified (DS) materials are casted to form grain boundaries with directions that are parallel to the primary loading axis of the blade. This results in an anisotropic material with particularly desirable mechanical properties in certain direction. This technique combined with the natural high strength and high temperature resistance of a nickel-based superalloy can be used in components to increase operating temperatures, and therefore efficiency of turbines, while maintaining or improving reliability.

A DS Ni-based superalloy is the candidate material of this study. Example DS superalloys are DS GTD-111, Rene 80H, IN738LC, MAR M247 and MAR M200. These materials contain columnar grains that can be oriented at any angle to consumer specification, though typically so that long grains are aligned with the primary axis of the blade.

If the material were to be examined in a local coordinate system relative to this orientation, the existence of mutually orthogonal axes would be observed, making DS materials orthotropic. As the mechanical properties of the two transverse directions are identical, the candidate material can be classified as transversely isotropic. In the global coordinate system, the material properties are a function of the orientation. In this study, grain orientations, θ, of 0°, 45°, and 90° are considered, which can be seen in Figure 3.1. In this figure, the dotted lines indicate the direction of the grains.

Furthermore, as the simulations conducted vary from 100°C to 950°C, these material properties are also a function of temperature. In ANSYS, mechanical properties of the material are inputted for various temperatures, and the program interpolates between them, allowing for a steady progression of material properties when temperature is gradually changing in the TMF cycle. Mechanical properties and the cycles used in calculations are selected to reflect the mid-life of the material. Focusing on the mid-life allows for post-hardening/softening that is a cyclically stable representation of the turbine component in service condition.

Stress and strain results for each simulation are taken with respect to the loading axis. This direction is independent of material orientation, so that the effects of the anisotropic material can be observed and compared.

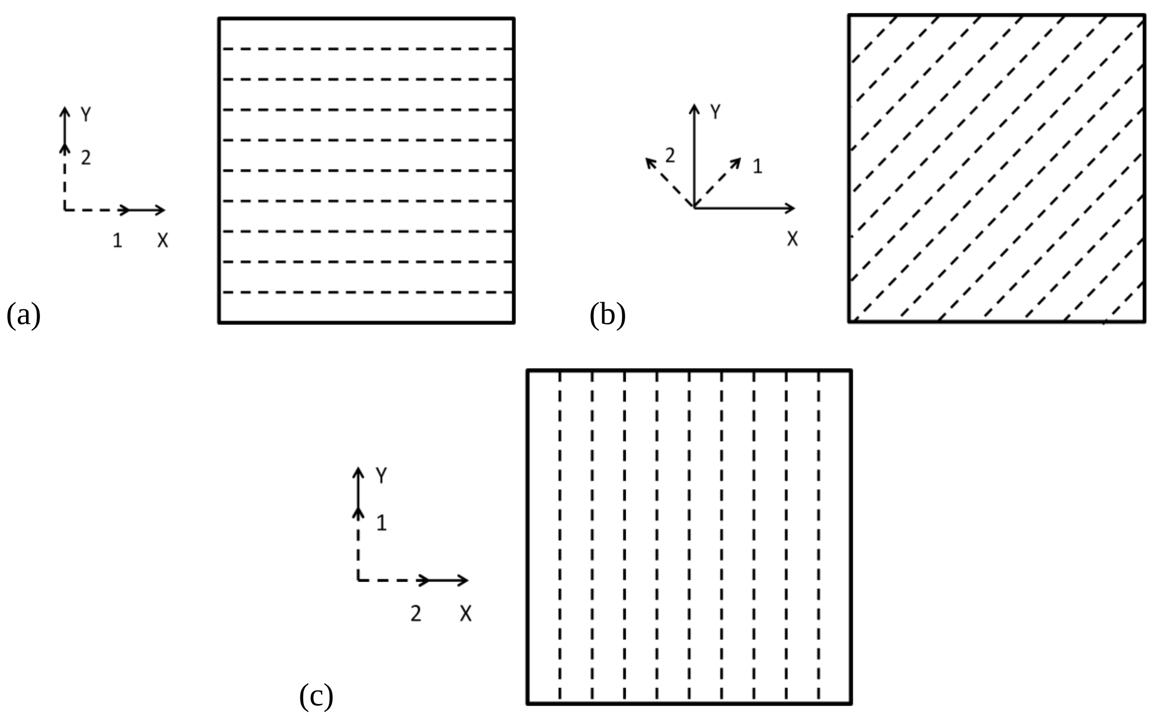


Figure 3.1: Sketch of Grain Orientation for (a) T-oriented [0°] materials, (b) 45° oriented materials, and (c) L-oriented [90°] materials

4. Finite Element Modeling Approach

The focus of this study on effects of a V-notch in thermomechanical fatigue is that of a broad and inclusive set of simulations that replicate the diverse load histories and temperature profiles used in engineering practice. These include the maximum and minimum cycle temperature, T_{max} *and* T_{min}, the strain range, $\Delta\varepsilon$, the angle of orientation, θ, to which the model is rotated, the strain ratio, R, hold times, t_{hold}, number of cycles, and phasing, φ. To capture such a large set of loading conditions, a parametric study was conducted in ANSYS 14.0 Mechanical APDL. APDL, short for ANSYS Parametric Design Language, is the FORTRAN-based programming equivalent to ANSYS Workbench, and allows simulations to be set up and conducted in a code-based environment.

Before testing the multi-element notched specimen model, the framework and process for the code was first created for a simple, single element cube. This model was essential to test the proposed code for the TMF cycle and to correlate TMF to isothermal conditions.

4.1 Un-notched Model

A single element model was also used to compare the stress and strain results of an isothermal test to that of a TMF case. The type of element used is a Solid185 element consisting of 8 nodes in a cubic array, which can be seen in Figure 4.1. Each side of the cube has a length of 1mm. This task was carried out to determine a mathematical relationship between the cases, and served as a stepping stone to the three-dimensional notched model. As any TMF model would need to account for variations in phasing, stress ratio, and other loading conditions, the complexity of the problem can be reduced by determining candidate relationships for a single element, rather than an entire multi-element structure.

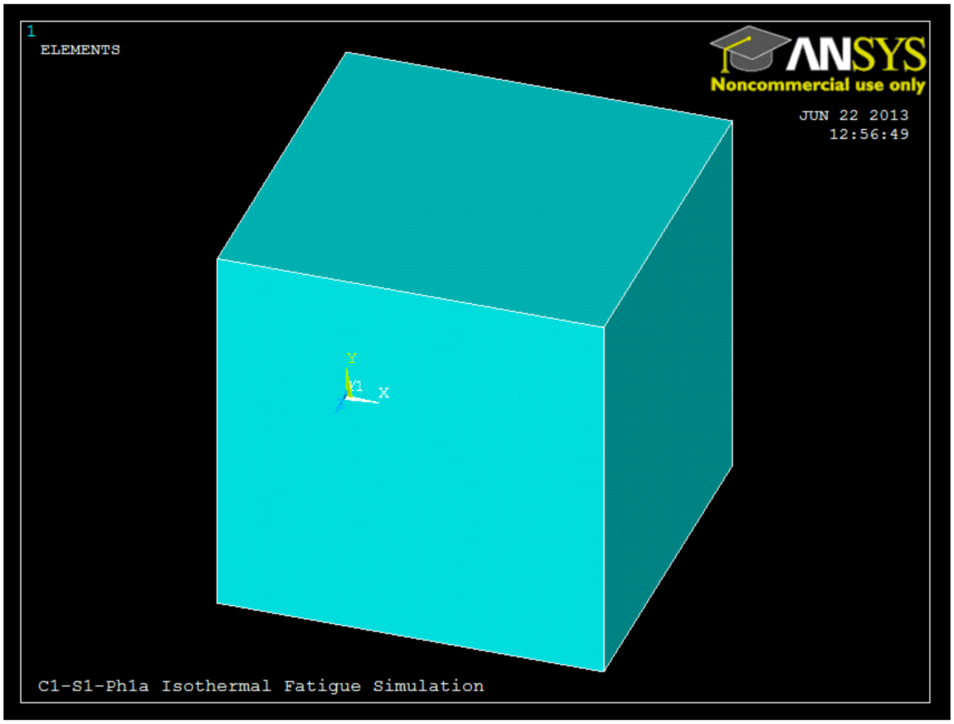


Figure 4.1: Single Element Structure Used in Un-notched Isothermal and TMF Parametric Tests

The finite element calculation of a single-element is relatively simple. As such, the solve time in ANSYS ranged from 10 seconds in simulations with no hold time and a low strain range, to 20 seconds in simulations with a longer hold time and larger strain range. Taking advantage of this speed, a large number of simulations could be conducted to encapsulate all cycle variations.

The single-element code created for these simulations allows for automated and parametric displacement-controlled testing of any combination of temperatures, T, strain ranges, $\Delta\varepsilon$, orientation, θ, and strain ratio, R. In this study, the strain range is tested from 0 mm/mm to 0.01 mm/mm of strain with intervals of 0.00025 mm/mm. Isothermal tests were conducted at 100°C, 750°C, 850°C, and 950°C. The valley temperature in TMF tests was set to 100°C in all cases, and peak temperatures were tested at 750°C, 850°C, and 950°C. In LCF simulations, strain is applied at a rate of 0.001 s^{-1}. For TMF tests, the rate of strain is determined by temperature range, which is cycled at a rate of 3° per second. This rate mimics the heating and cooling limitations in a physical experiment.

Being the most common strain ratios, zero-to-tension (Figure 4.2a), zero-to-compression (Figure 4.2b), and completely reversible (Figure 4.2c) cases were tested. These would have a strain ratio, R, of 0, $-\infty$, and -1, respectively. The angles under consideration are 0°, which is equivalent to the transverse direction, 90°, which is equivalent to the longitudinal direction, and 45°. In order to simulate real-world conditions, each cycle either contain no hold times, or contain a single 20 hour compressive or tensile hold at the peak temperature. The single hold would be equivalent to a turbine producing power for a 20 hour period before being shut off.

The variations in testing conditions allowed for approximately 7200 different combinations. A summary of these variations can be seen in Table 4.1. The ANSYS parametric code used in this study can be found in the appendix.

Table 4.1: Parametric Test Parameters for Un-notched Model

Condition, Symbol (Units)	Value
Strain Range, $\Delta\varepsilon$ (mm/mm)	0.0000 - 0.0100
LCF Isothermal Test Temperatures, T (°C)	100, 750, 850, 950
TMF Peak Temperatures, T_{max} (°C)	750, 850, 950
TMF Valley Temperature, T_{min} (°C)	100
TMF Phasing, φ	In-phase, Out-of-phase
Strain Ratio, R (mm/mm)	0, -1, $-\infty$
Hold Time, t_{hold} (hr)	0, 20
Grain Orientation, θ (°)	0, 45, 90

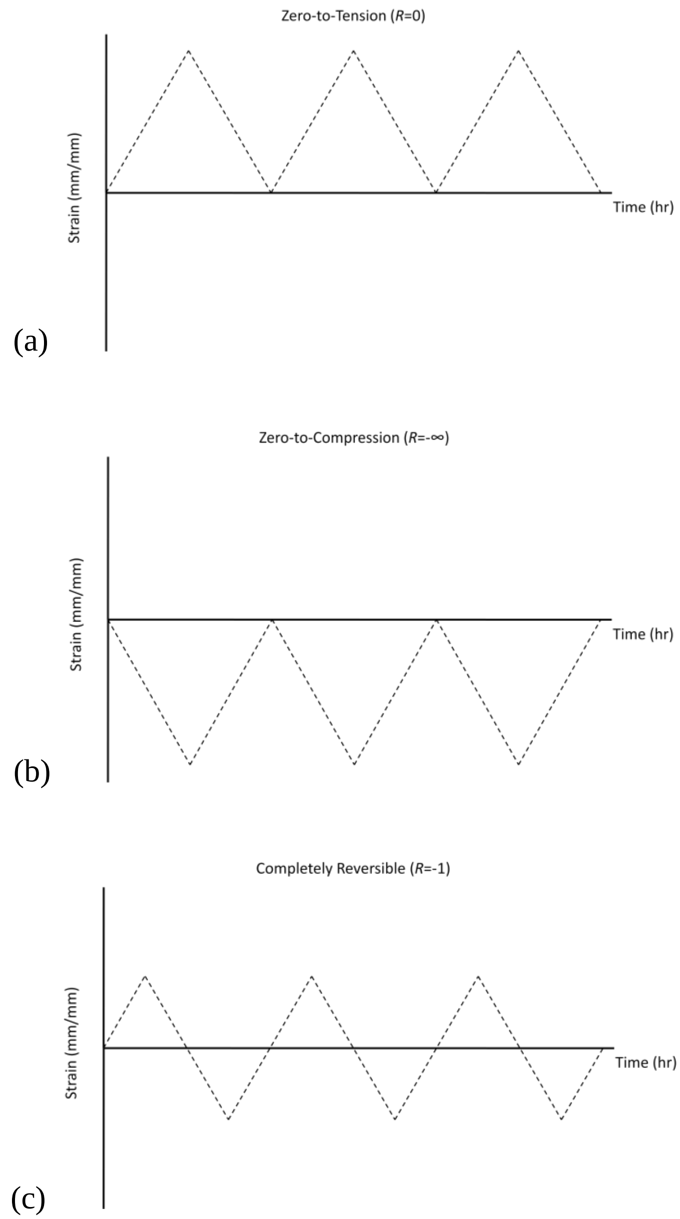


Figure 4.2: (a) Zero-to-tension, (b) zero-to-compression, and (c) completely reversed strain ratios

4.2 Notched Model

The multi-element model is that of a standard ASTM E8 test specimen with a V-shaped notch in the center of the gage section. Specimen dimensions are matched with existing samples of a concurrent notched TMF lifing study [Karl, 2003] and can be seen in Appendix A.

Originally, axis-symmetric conditions were used to revolve a quarter of a two-dimensional slice of the specimen to simulate the effect of a cylindrical specimen. Although this assumption would be correct in terms of the specimen shape, it would homogenize the microstructure of the material. When the specimen is subjected to a strain that is not in the longitudinal or transverse directions, the specimen would be modeled with the grain directions mirrored about the vertical axis, meaning that the grains would not be consistent throughout the specimen. This mismatch can be seen in Figure 4.3.

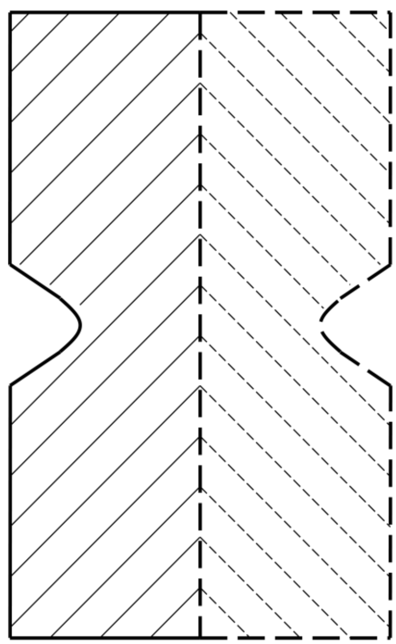


Figure 4.3: Hypothetical Grain Boundary Comparison of Modeled Portion and Axis-symmetric Portion

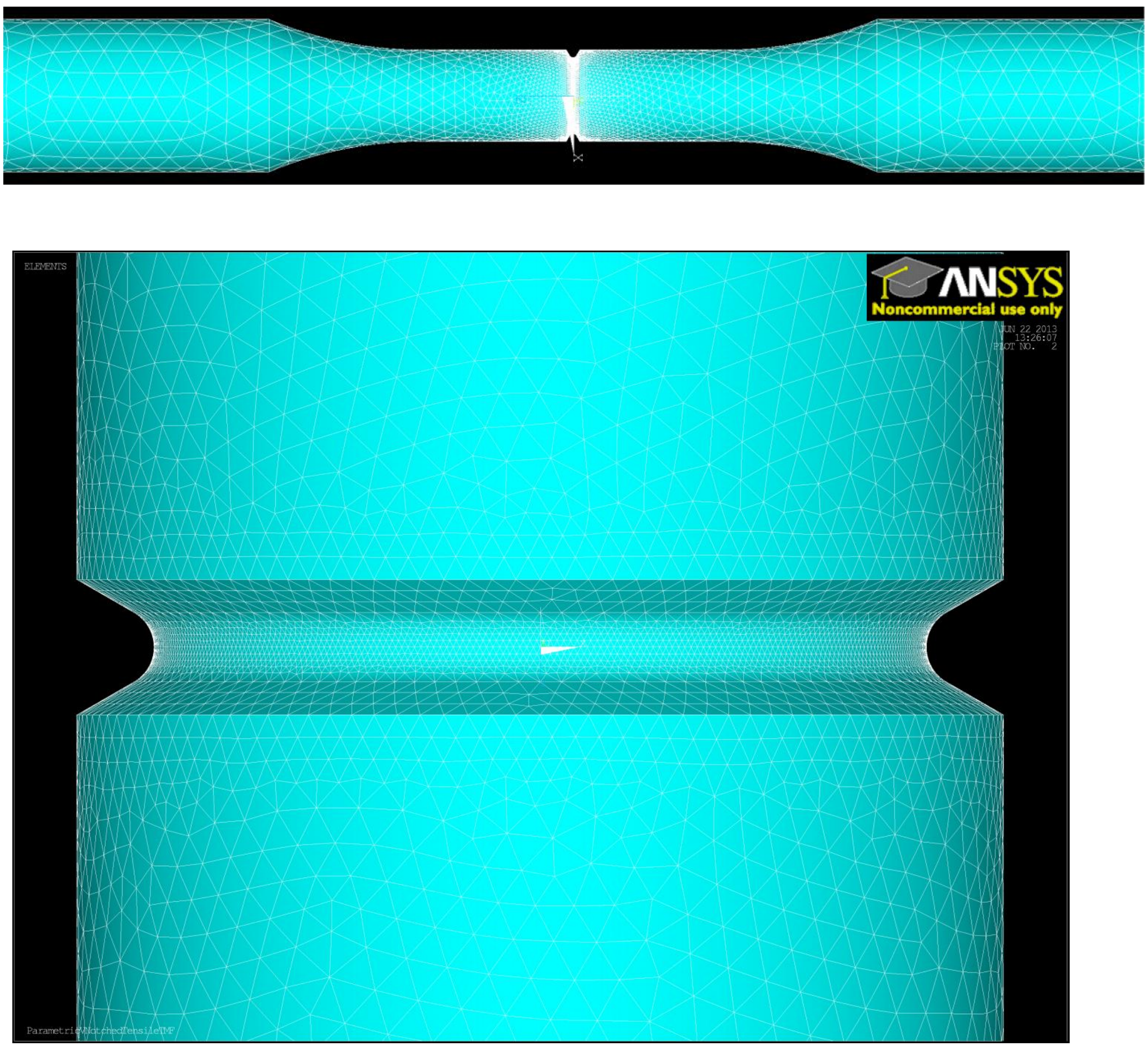
To resolve this problem, the axis-symmetric two-dimensional model was replaced with a three-dimensional model of a specimen. The orthotropic material properties allows for symmetry along one of the transverse directions, so only half the specimen is modeled to save processing power. This cut also allows for a direct visual analysis during the development of the plastic zone around the notch. To confirm that symmetry was correctly applied, this model was compared to a full three-dimensional model, which showed less than 1% difference in resulting data. The completed model is meshed using Solid187, 10-node tetrahedral elements, with constraints to simulate the proper boundary conditions. In total, the model contains 91737 nodes and 60701 elements. The finite element model of the notched specimen used in this study, as well as a magnified view of the notch section, can be found in Figure 4.4. The notch section contains 64% of the elements.

The structure of the multi-element code uses the same basic framework as the single-element code. However, as the focus of the study is to find the relationship between the local and remote stress, the input strain range cannot be that of the notch tip. Therefore, estimations of the remote strain are used as the selection procedure for each displacement. Resulting stress and strain data is collected and compared for the notch tip and the remote location. This remote location was chosen to be the grip section. Although location for a strain gage, it would allow output from the test frame load cell and displacement of the cross bar to be the only data collection necessary.

Due to the length of time required to conduct three-dimensional simulations containing a large quantity of elements, a smaller portion of tests were carried out. A total of 120 variations were conducted, which are listed in Table 4.2.

Table 4.2: Parametric Testing Parameters for Notched Model

Condition, Symbol (Units)	Value
LCF Isothermal Test Temperatures, T (°C)	100, 750, 950
TMF Peak Temperatures, T_{max} (°C)	750, 950
TMF Valley Temperature, T_{min} (°C)	100
TMF Phasing, φ	In-phase, Out-of-phase
Strain Ratio, R (mm/mm)	0, -1
Hold Time, t_{hold} (hr)	0
TMF Strain Rate, $\dot{\varepsilon}$ (°/s)	3, 6
Grain Orientation, θ (°)	0, 45, 90



(a)

(b)

Figure 4.4: (a) Multi-Element Structure Used in Notched Simulations (b) Magnified View of Notched Area

4.3 Data Analysis and Organization

There are two primary methods by which data are plotted for presentation and analysis. The first is a standard stress-strain hysteresis curves of individual test cases. Hysteresis curves provide insight on the strain applied over time, and the resulting stress at that time. With these curves, material response for an isothermal load can be compared to that of a TMF load as the cycle progresses. Hysteresis curves also demonstrate the progression of the stress between cycles, which is particularly important when analyzing data sets that contain a peak or valley hold time. In this study, hysteresis data are collected for each test variation for a total of three cycles. This amount was chosen after a series of initial runs confirmed that the material response stabilized into a common trend after the second cycle. The only exceptions to the number of cycles are the hysteresis curves collected for ten cycles. This small set of hysteresis curves are used to determine the effect of creep in no-hold TMF tests.

Data are also presented in a unique plot where maximum and minimum stress is compared to their respective strain range. Individual graphs are created for each cycle number, maximum temperature, strain ratio, and hold time. Each plot accounts for the maximum and minimum stresses in the isothermal response at the high temperature, isothermal response at the low temperature, and IP TMF and OP TMF. The source of these plots is modeled in Figure 4.5. This data has proven to be critical in determining the correlation between isothermal and TMF conditions, as it allows for a direct comparison at every desired strain range; therefore, results of this study can be used to determine maximum and minimum stress separately, and if desired, these values can be used to find the stress range and mean stress. Each plot in this report contains normalized data.

In order to effectively convey the findings in this study, a uniform format will be used to present the data and provide discussion. First, a zero-to-tension IP data set of the second cycle with a peak temperature of 950°C will be compared to minimum and maximum isothermal data with respect to the elastic response, plastic response, creep response, and cycle number. Then variations in temperature will be outlined, followed by a change in cycle phasing. Once this has been completed, different strain ratios will be accounted for, and hold times will be changed. In Chapter 5, each of these test conditions will first be analyzed graphically so that trends in the data are clearly expressed. Using the insight provided by these plots, discussion of the material response will be conducted, and an approximation method for individual sections of the response will be presented. Chapter 6 unifies these sections so that an approximation for the maximum and minimum stress under TMF loading can be made. Chapter 7 is a presentation of data collected from the notched FE model. Also included in this chapter is an attempt to combine the TMF approximations of Chapter 6 with classical approaches to define an non-isothermal, non-local approach to notch stress.

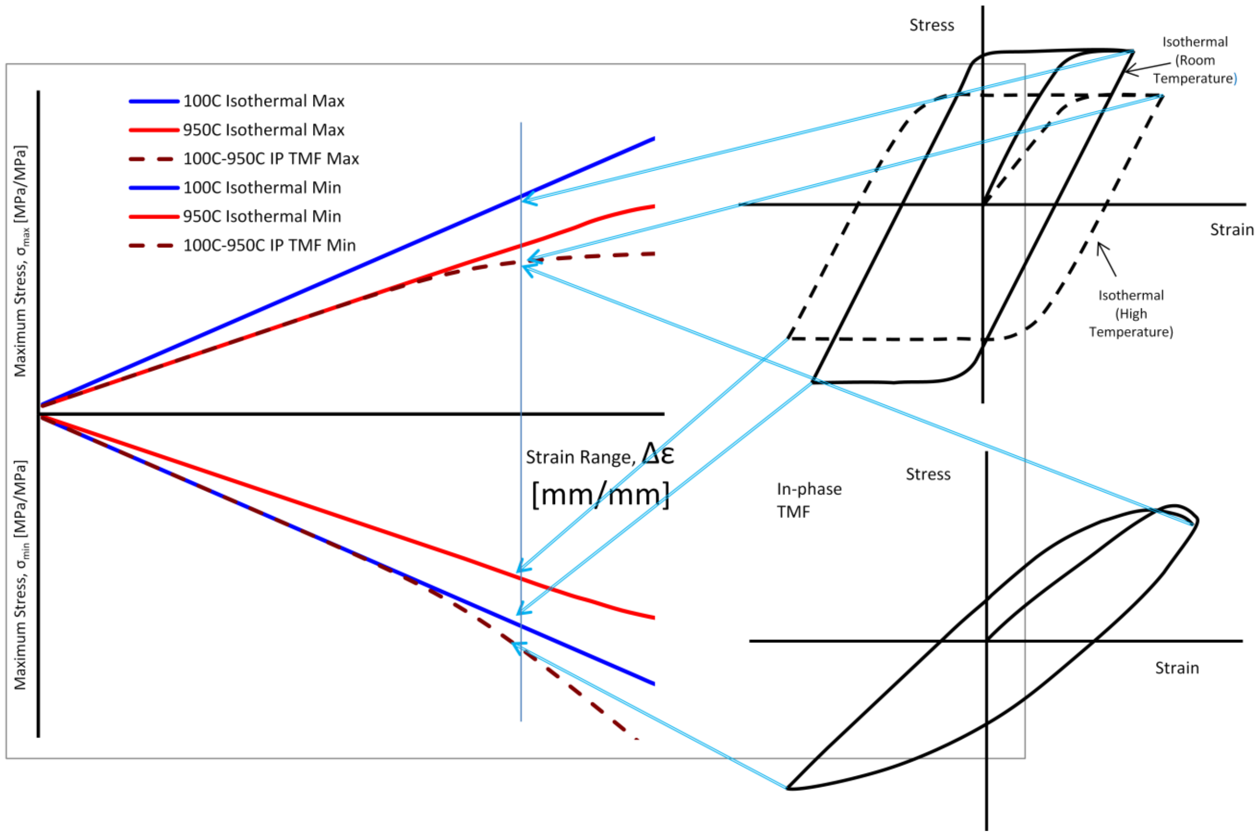


Figure 4.5: Sample Plot of Minimum/Maximum Stress vs Strain Range With Originating Hysteresis Loops

5. Un-notched Simulations and Results

5.1 In-phase, Non-isothermal Response Without Hold

Data in this section is collected from simulations of a TMF loading with a peak temperature of 950°C. The load is applied IP with a zero-to-tension stress ratio and the cycle contains no hold time. Figure 5.1 compares the maximum and minimum stress with strain range for the first cycle. In each of these plots, the Ramberg-Osgood relationship can be used to accurately represent isothermal data. Though the first cycle contains data that has not stabilized, it should be noted that the maximum stress for the TMF curve is bound by the two isothermal curves. This would mean that the maximum stress does not occur at the peak temperature, but instead, at a lower temperature where the elastic modulus and yield strength is higher. This can also be seen in a sample hysteresis loop with these loading conditions in Figure 5.2, where the maximum stress is located before the maximum strain and a short dip in stress occurs even though strain is increased at a steady rate with no hold time. The conservative approach to estimating the stress in this first cycle would be to use properties at the lower temperature. In further discussions, the first cycle will be ignored.

The second cycle of this load condition, plotted in Figure 5.4, exhibits a trend that is consistent across all strain range to maximum/minimum stress plots developed in this study. Graphically, this trend can be represented by segmenting the plot into three distinct regions. This can be seen in Figure 5.3, which is created from identical testing conditions, but includes a larger set of strain ranges. Region I can be described as the collection of strain ranges in which the TMF response remains elastic. I the plot, the maximum stress is linear and the minimum stress is zero. Region II contains strain ranges in which the maximum stress becomes non-linear, indicating plasticity has developed. The deformation occurring in this section leads to a compressive stress when the displacement controlled model is forced back to the original position. In this region, the minimum stress does not exceed the compressive yield strength, which is graphically represented as a linear function. Region III begins when the compressive yield strength has been met and an extra level of plasticity is created. In turn, this additional plasticity affects the response of the maximum stress, graphically observed as a ramp in stress.

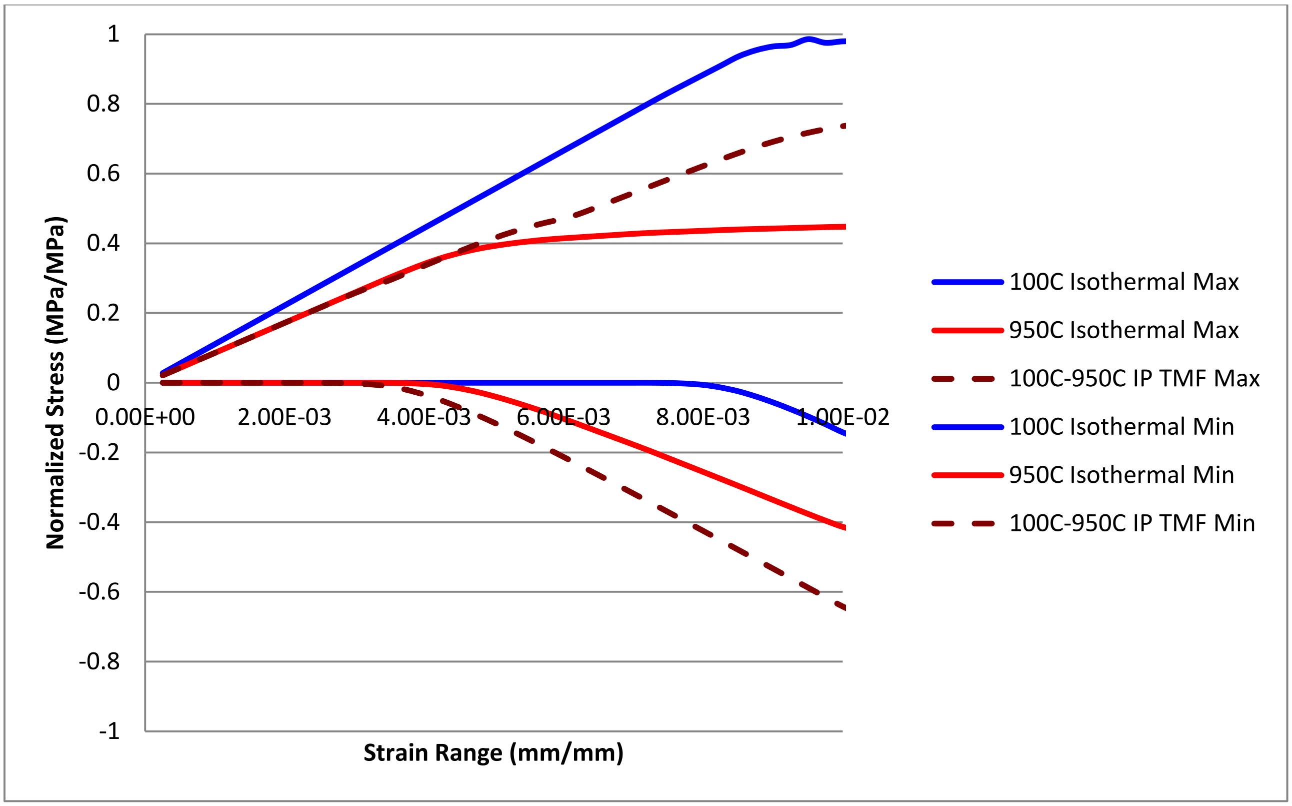


Figure 5.1: First Cycle Minimum and Maximum Response for a 100C-950C Zero-to-Tension IP TMF Load

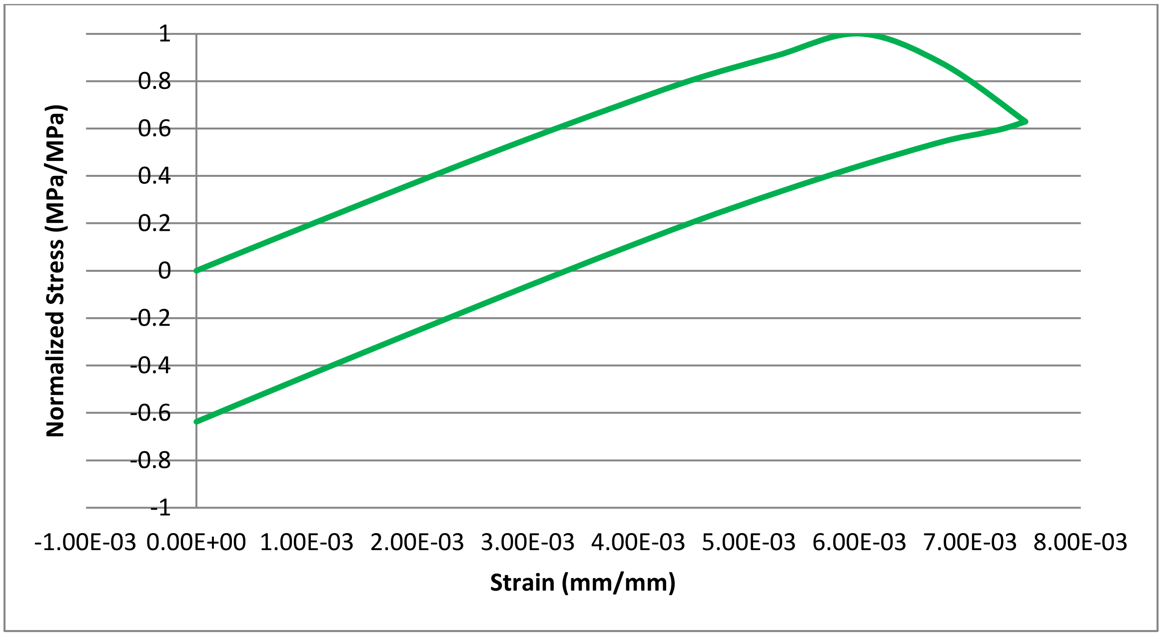


Figure 5.2: First Cycle Hysteresis Loop for a Zero-to-Tension 100C-950C IP TMF Load with a Strain Range of 0.0075 mm/mm

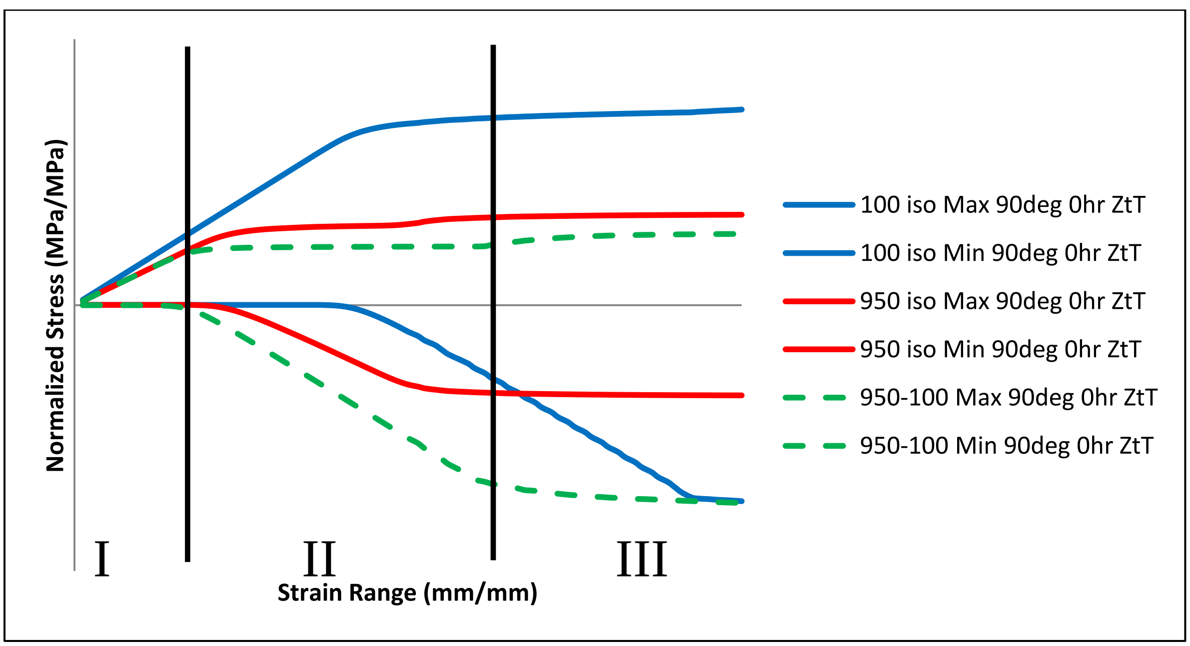


Figure 5.3: Extended Strain Range Plot Modified to Show Region I, Region II, and Region III

By focusing on strain ranges where the elastic conditions are maintained throughout the entire TMF cycle (Region I), the simple observation can be made that the maximum stress in IP loading is equivalent to the maximum stress in isothermal loading at the peak temperature. This correlation holds for all IP TMF before plasticity is introduced. As no permanent deformation occurs in these zero-to-tension cycles, the minimum stress is zero.

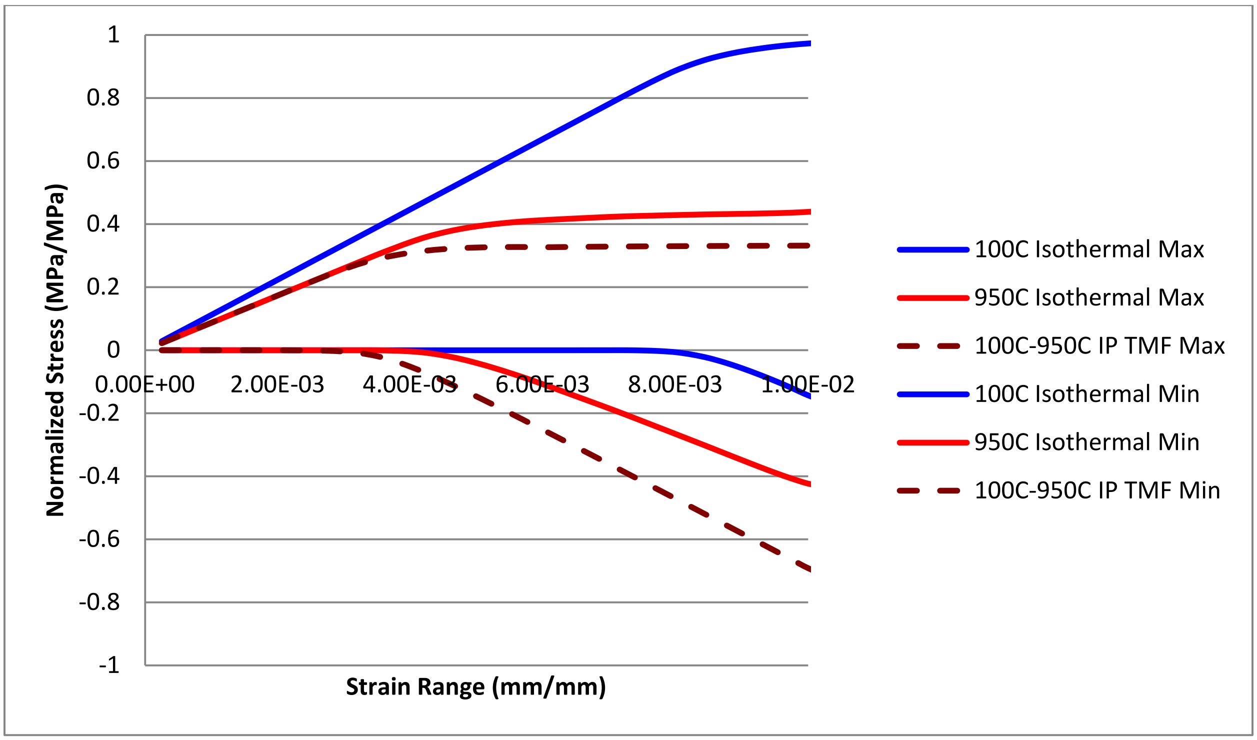


Figure 5.4: Second Cycle Minimum and Maximum Response for a Zero-to-Tension 100C-950C IP TMF Load

The difference between isothermal and non-isothermal response begins in Region II with the onset of first cycle plasticity. The TMF curve begins to diverge from the peak temperature isothermal curve at a location where the maximum stress is lower than the yield strength of the material at the peak temperature, as shown in Figure 5.4. This means that the material begins to plastically deform before the maximum temperature and maximum strain is reached. By observing the hysteresis plot of a sample test in Figure 5.2, the cause is revealed to be a product of the mismatch of elastic modulus and yield strength over time. As temperature increases, the elastic modulus and yield strength decrease, though some level of stress has already been created. That is to say, when starting at a lower temperature where the elastic modulus is higher, a higher stress will accumulate given a constant strain rate. When the temperature increases, the rate at which stress is created starts to slow, but the material has already accumulated some amount of stress. At some point in the ramp up stage of the cycle, that amount will exceed the yield strength of the material at that particular temperature. If the cycle time were very slow, it is possible that stress relaxation at the higher temperatures would compensate for this effect.

Considering Figure 5.4, the maximum stress in the material yields at a different location, but still displays a similar trend as the peak isothermal counterpart. Earlier it was mentioned that Ramberg-Osgood can be used to model the peak stress in the isothermal case, and given the similarity of the isothermal and non-isothermal curves, it can be theorized that given the correct constants, Ramberg-Osgood can also be applied to this TMF case. Since isothermal constants cannot be used for this purpose, a separate set needs to be derived, and if possible, correlated with isothermal constants. This is covered in detail in the following section.

The relationship for the minimum stress can also be determined. Given the nature of zero-to-tension stress ratio, the minimum stress remains at zero until plasticity is introduced. When the yield point is reached and the curve becomes elastic-plastic, the minimum stress begins to decrease at a steady rate. This rate at which it decreases is equivalent to the elastic modulus at the lower temperature, which would be the temperature at which the minimum is reached. The trend is also apparent in isothermal temperatures. This relationship holds until the minimum stress reaches a compressive yield strength, where the maximum stress will also become affected. This was labeled earlier as Region III. However, this was noted to occur at strain ranges exceeding 0.01 mm/mm, which is beyond the scope of this study.

The cycle number under study is also a contributing factor to maximum and minimum stress response under TMF loading. In the plot of the second cycle in Figure 5.4 and the third cycle in Figure 5.5, a small but noticeable drop in the maximum stress of the IP TMF response between each cycle is observed. This is directly compared in Figure 5.6. The amount by which this vertical shift occurs varies from cycle to cycle, but maintains a gradual decline. To better demonstrate this occurrence, an extended, 10-cycle hysteresis loop is created for one such test condition and target strain range. As can be seen in Figure 5.7, this shift takes on a power law relationship. Plotting only the maximum stress for each cycle after the first, unstabilized loop against cycle time, and fitting a power law trend-line, a near-perfect fit can be made (Figure 5.8).

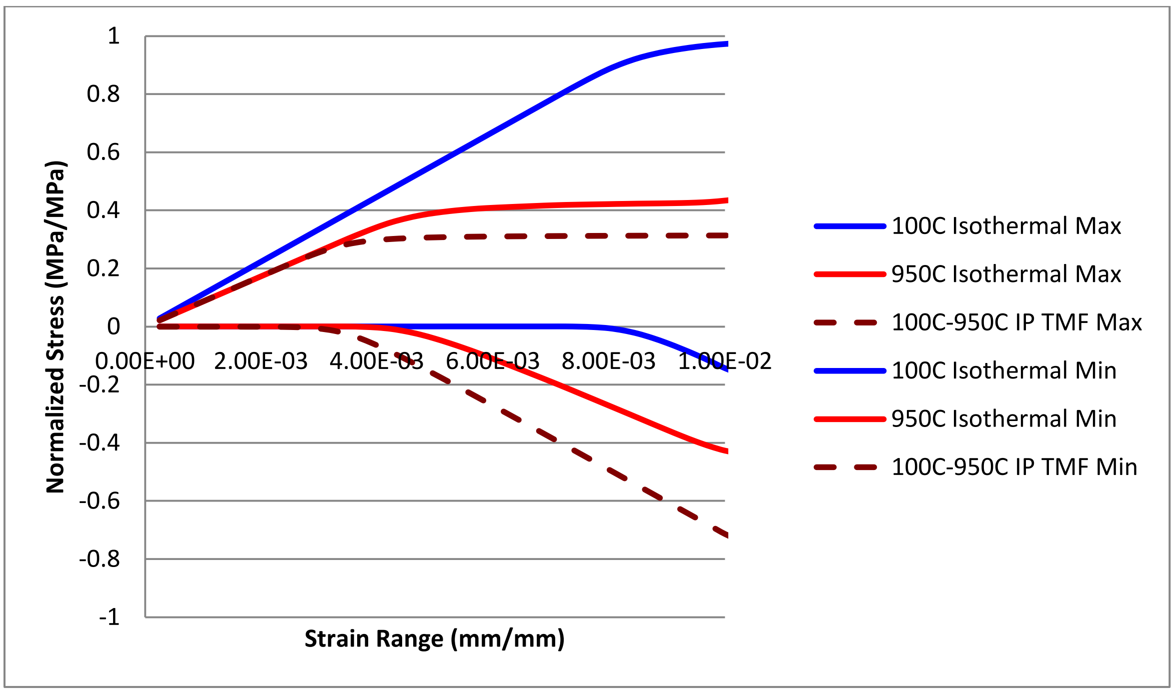


Figure 5.5: Third Cycle Minimum and Maximum Response for a Zero-to-Tension 100C-950C IP TMF Load

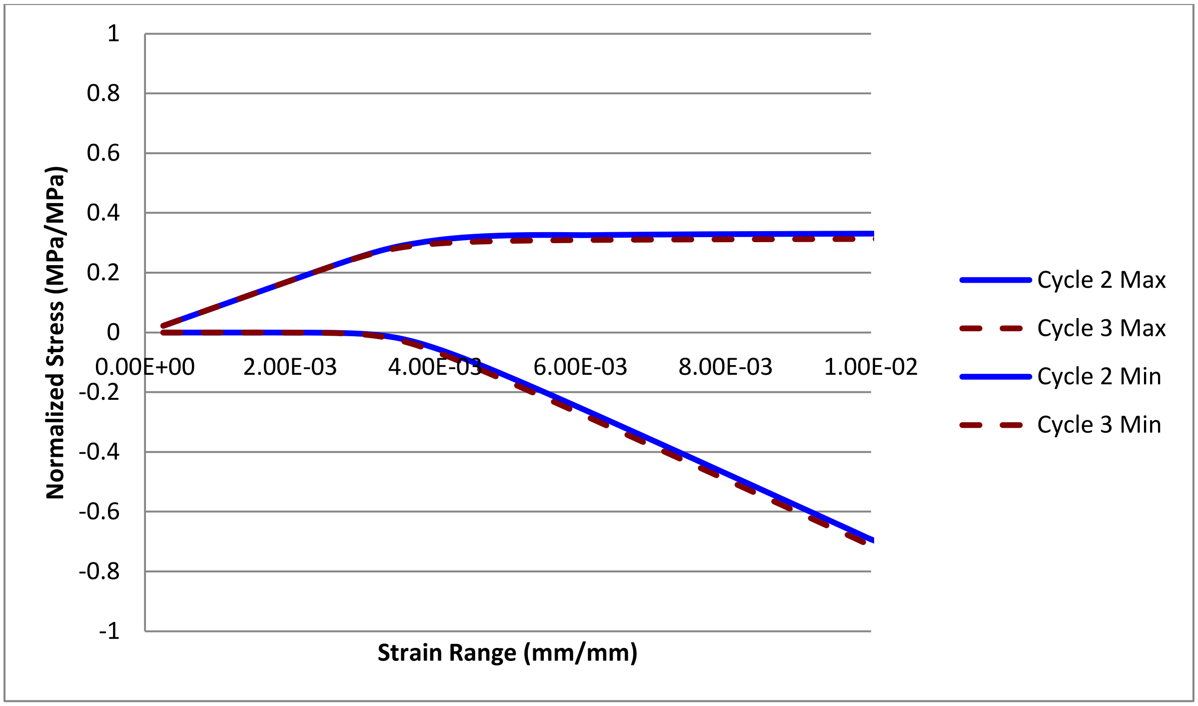


Figure 5.6: Comparison of Second and Third Cycle Minimum and Maximum Response for a Zero-to-Tension 100C-950C IP TMF Load

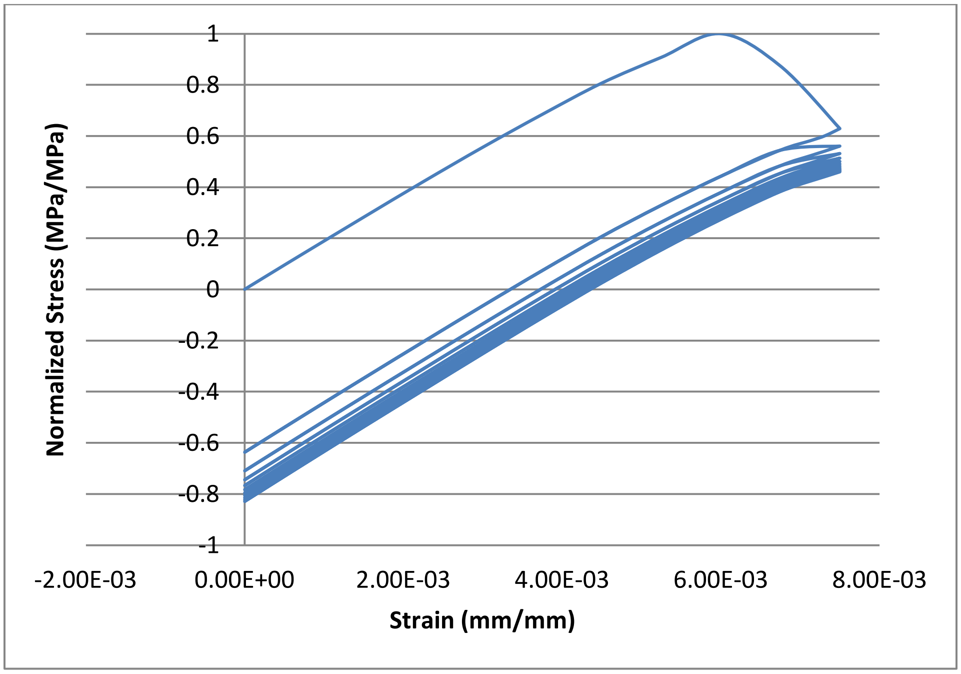


Figure 5.7: 10 Cycle Hysteresis Loop for a Zero-to-Tension 100C-950C IP TMF Load with a Strain Range of 0.0075 mm/mm

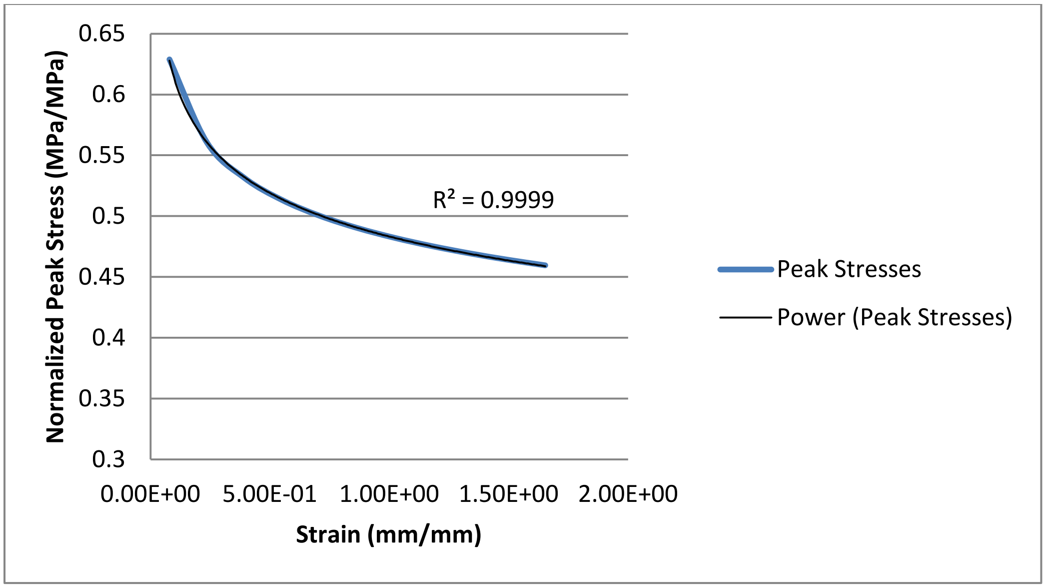


Figure 5.8: Peak Stresses for 10 Cycle Hysteresis Loop for a Zero-to-Tension 100C-950C IP TMF Load with a Strain Range of 0.0075 mm/mm

The effect of creep can also be modeled with a similar trend using Norton's Power Law, making stress relaxation a natural starting point for analysis. Norton creep can be estimated using the formula

$$\dot{\varepsilon}_{creep} = A\sigma^{n} \qquad [5.1]$$

where $\dot{\varepsilon}_{creep}$ is the creep strain rate, σ is the stress, and *A* and *n* are material constants unique for each temperature. Using a fundamental approximation that during constant strain tests

$$\dot{\varepsilon}_{el} + \dot{\varepsilon}_{creep} = 0 \qquad [5.2]$$

where the elastic strain rate, $\dot{\varepsilon}_{el}$, can be converted to stress rate, $\dot{\sigma}$, using variation of Hooke's Law

$$\dot{\varepsilon}_{el} = \frac{\dot{\sigma}}{E} \qquad [5.3]$$

to form

$$\frac{\dot{\sigma}}{E} + A\sigma^n = 0 \qquad [5.4]$$

Assuming the initial time and initial stress are zero and using material properties at the peak temperature, Equation [5.4] can be solved for the stress as a function of time, *t*, yielding the formula

$$\sigma = [(\mathrm{n}-1)\,\mathrm{EAt}]^{\frac{1}{(1-n)}} \qquad [5.5]$$

Here, the stress accumulated from creep over time can be found. Solving for values for time that occur at the same point in each cycle, such as the location of maximum strain, and subtracting the results of the previous cycle would estimate the value of stress relaxation the material experiences. Stress relaxation is the decrease in stress due to creep at elevated temperatures which can occur without change in total strain.

Inputting the time of peak strain gathered from the IP TMF hysteresis data selected previously in Figure 5.7 and the creep constants at the higher temperature into Equation [5.5], results in values for an approximate stress relaxation. These values are nearly identical to that of the load drop, which can be seen in Figure 5.9, and allows for the assumption that this drop in stress is the stress relaxation due to creep. The minor difference in value can be attributed to the use of creep constants pertaining to the peak temperature. As temperature is cycled in TMF, this assumption is not exact, but is mitigated due to the fact that the cycle does not contain a dwell. This approximation could be improved, however the benefit would be almost negligible, and using the peak temperature provides some degree of conservatism in the result. Therefore, the drop in stress between cycles can be approximated as the stress relaxation at the peak temperature calculated using the time for each cycle in concert with Equation [5.5] and subtracting the results.

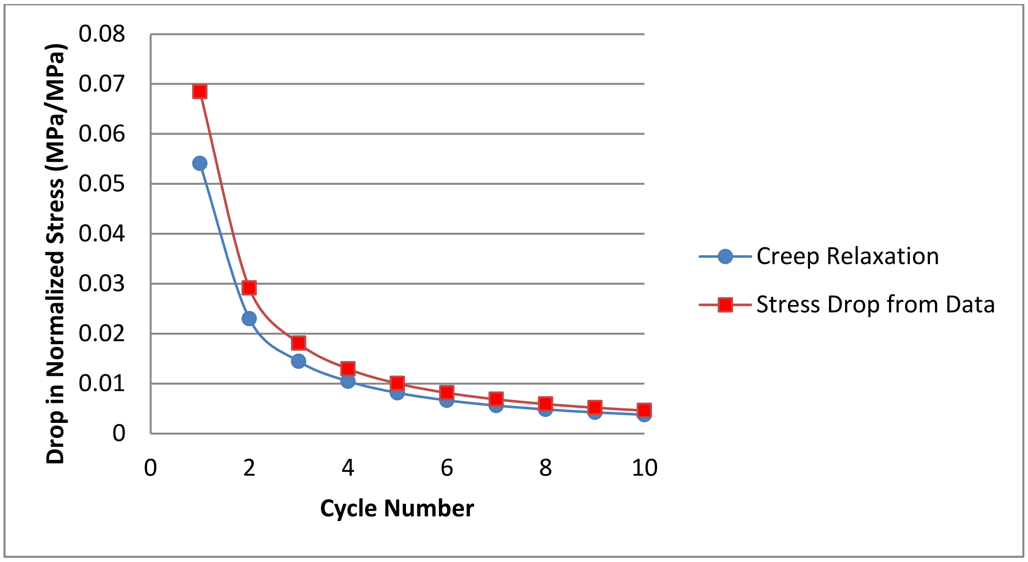


Figure 5.9: Comparison in Drop of Peak Stress and Creep Stress Relaxation at 950°C Per Cycle for a Zero-to-Tension 100°C-950°C IP TMF Load with a Strain Range of 0.0075 mm/mm

5.2 Variation in Temperature

The significance of temperature and the resulting change in the maximum and minimum stress is studied using peak temperatures of 750°C and 850°C. Shown in Figure 5.10 and Figure 5.11, respectively, the response exhibits different values of stress than that of Figure 5.4. However, the response maintains the same trends and observations covered previously.

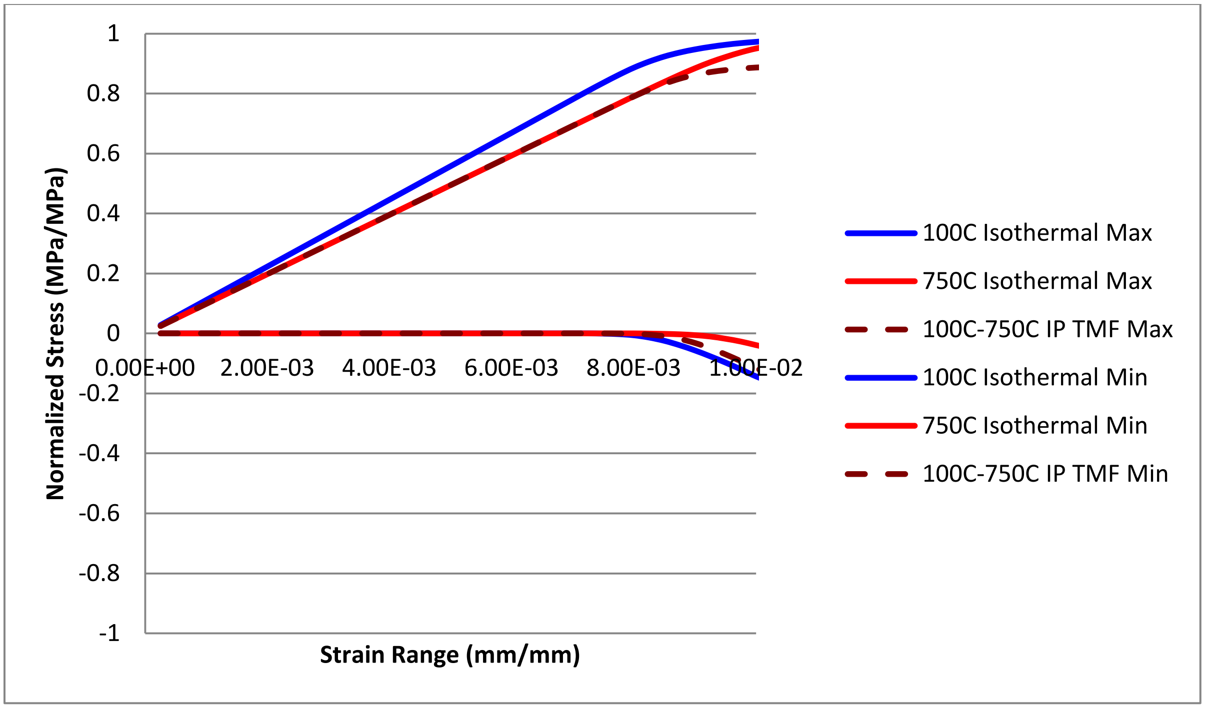


Figure 5.10: Second Cycle Minimum and Maximum Response for a Zero-to-Tension 100C-750C IP TMF Load

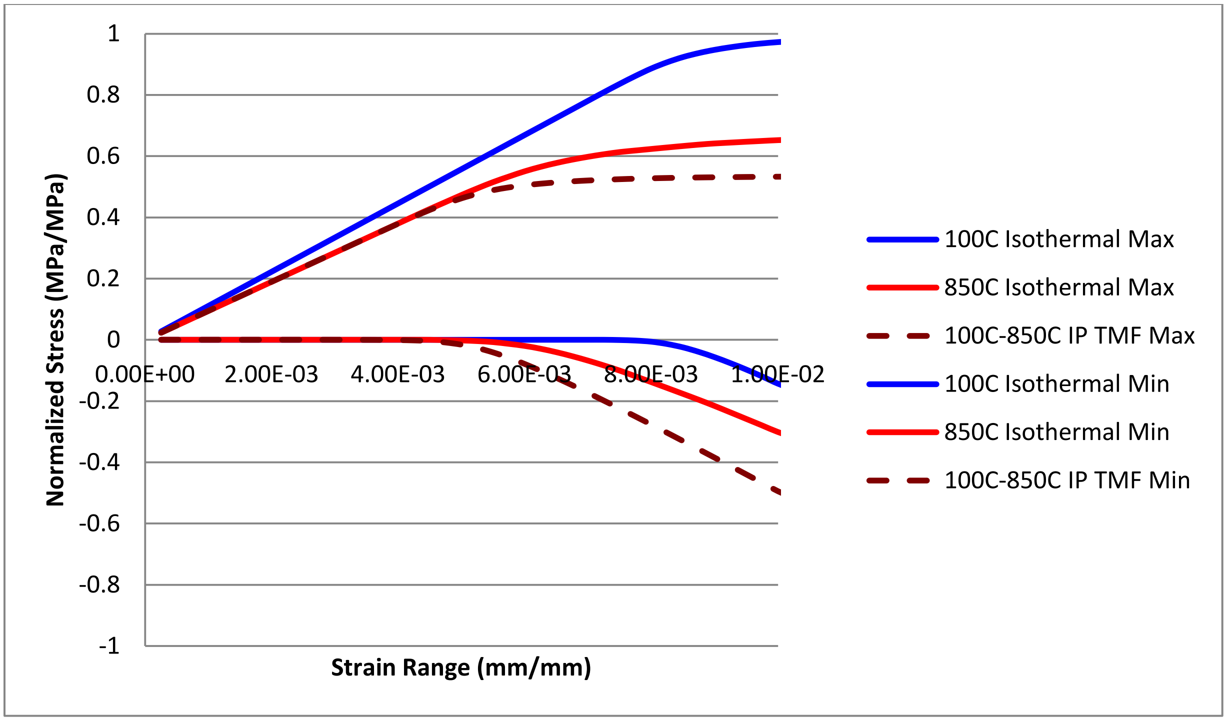


Figure 5.11: Second Cycle Minimum and Maximum Response for a Zero-to-Tension 100C-850C IP TMF Load

The elastic modulus at the peak temperature can still be used for the elastic portion, and although the values are different, Ramberg-Osgood can still be used to approximate the maximum stress. Using data from a variety of temperatures, a correlation between the isothermal and non-isothermal IP results has been found through the Ramberg-Osgood constants. First, a homologous modulus, *B,* is defined as

$$B = \frac{E_{iso,\max}}{E_{iso,\min}} \qquad [5.6]$$

where $E_{iso,max}$ is the elastic modulus at the maximum temperature and $E_{iso,min}$ is the elastic modulus at the minimum temperature. Using the homologous modulus, effective K^* and n^* constants can be calculated from the Ramberg-Osgood K' and n' constants of the material at the maximum temperature, where

$$K^* = BK' \qquad [5.7]$$

$$n^* = Bn' \qquad [5.8]$$

These IP TMF effective constants are used with the traditional Ramberg-Osgood relationship in Equation [2.6] to form the relationship

$$\Delta\varepsilon = \frac{\sigma_{\max}}{E} + \left(\frac{\sigma_{\max}}{K^*}\right)^{\frac{1}{n^*}} \qquad [5.9]$$

where $\Delta\varepsilon$ denotes the strain range and σ_{max} denotes the maximum stress.

It is interesting to note that if this approximation is used to determine the stress in the first cycle, the result is the stress at the peak temperature of this cycle, not the peak stress. However, if the calculated stress were to be compared with the peak stresses of later cycles, the same power law relationship holds. This means that the correlation between the drop in stress between cycles and the stress relaxation model also holds. Thus, even though the actual peak stress in the first cycle cannot be determined with this approximation, a fictitious peak stress (which can be estimated as the stress at the peak temperature) can be found. Using fictitious peak stress, and the stress relaxation model, the location of the second cycle, including the stress drop, can be determined.

This is done by incorporating the total amount of stress relaxation up to the cycle in question directly into the effective K^* constant. Therefore, the true K constant for the model is

$$K^{**} = K^{*} - \sigma_{relaxed} \qquad [5.10]$$

where σ_{relax} is the total stress relaxation accumulated over the previous cycles.

Application of Equation [5.9] can be compared to IP TMF results for 100°C-750°C in Figure 5.12. The results show a 0.9% variation with the FE analysis. IP TMF results for 100°C-850°C in Figure 5.13 show a 7.1% variation. Results for a peak temperature of 950°C show a 4.9% variation in Figure 5.14. Though the model is a simple modification using empirical observations, the results closely match the simulated data. Stress-strain hysteresis plots provide limited insight to the source of this accuracy, but it clear that the creep response is a driving factor. The effect of underlying material mechanisms, creep response, and the contribution of temperature-dependent material properties to the modification will remain a topic of continued research.

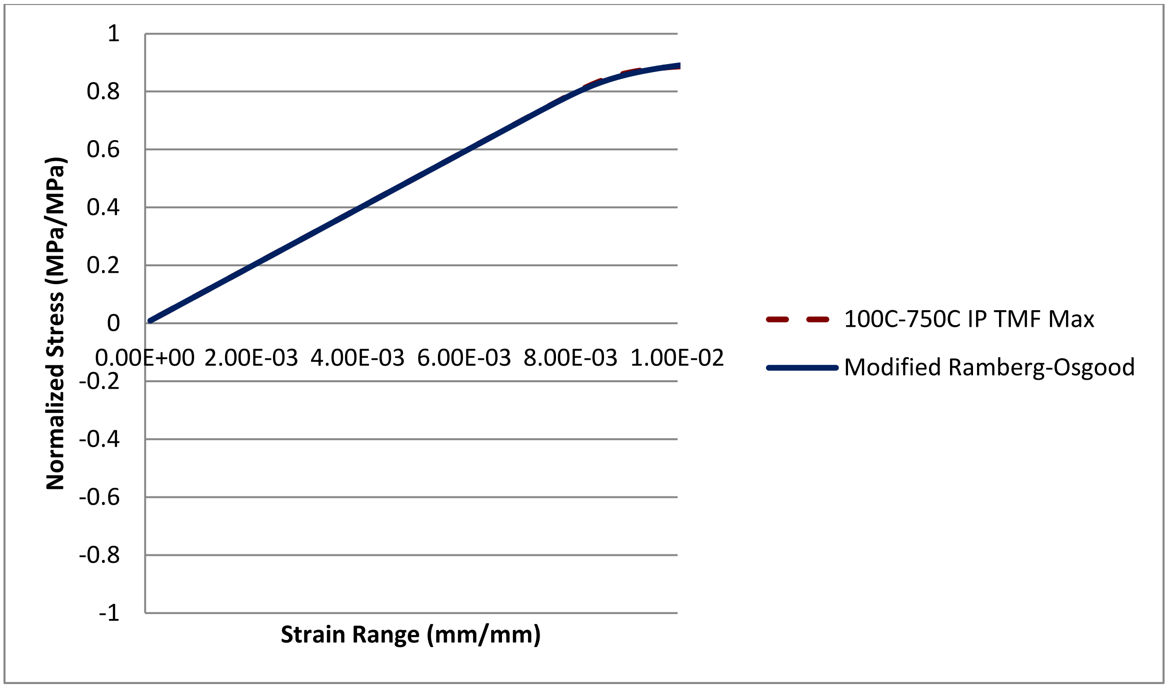


Figure 5.12: FEM Results Compared With Analytical Model for Second Cycle Minimum and Maximum Response for a Zero-to-Tension 100C-750C IP TMF Load

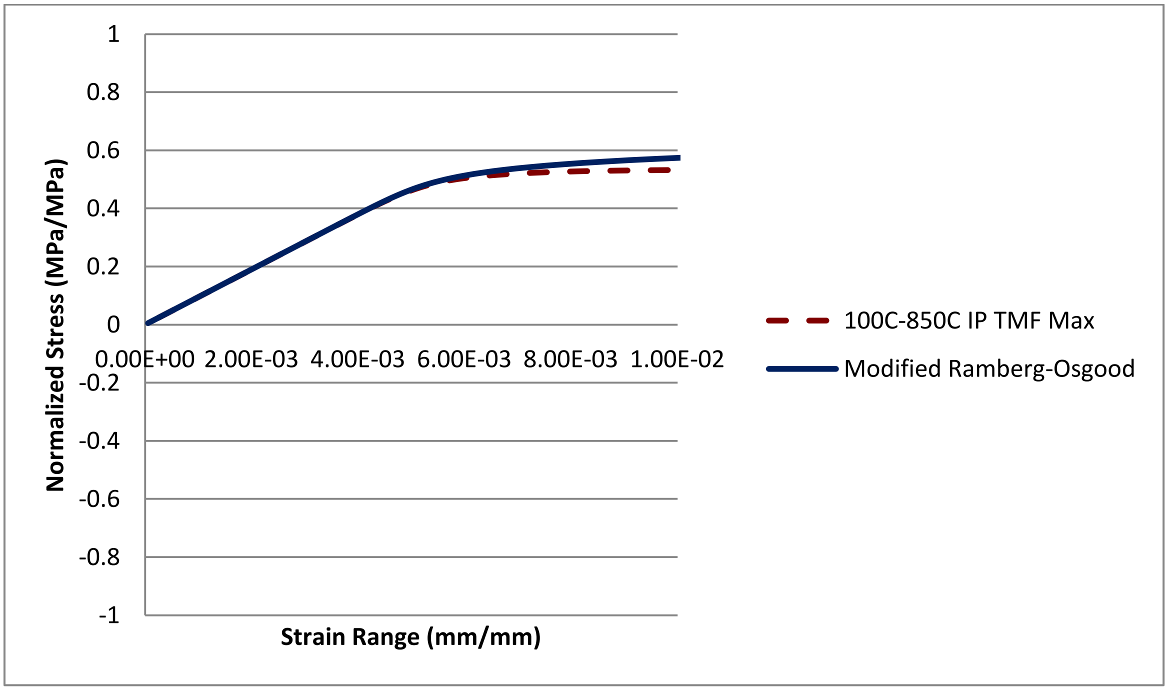


Figure 5.13: FEM Results Compared With Mathematical Model for Second Cycle Minimum and Maximum Response for a Zero-to-Tension 100C-850C IP TMF Load

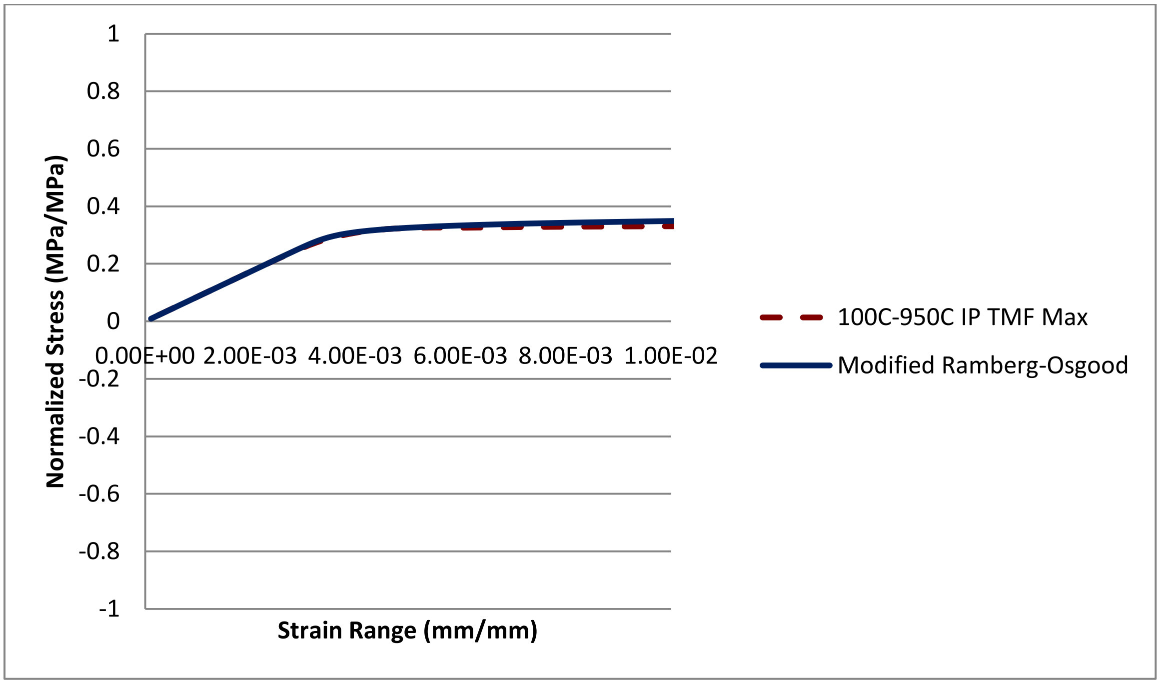


Figure 5.14: FEM Results Compared With Mathematical Model for Second Cycle Minimum and Maximum Response for a Zero-to-Tension 100C-950C IP TMF Load

5.3 Variation in Phasing

The temperature at which the displacement-control reaches a peak value is also an important factor when studying the effect of TMF. Figure 5.15 includes data from zero-to-tension OP TMF testing with a maximum temperature of 950°C. Results show that the curve representing the maximum strain for the OP TMF test condition is identical to that of the minimum temperature isothermal stress curve. In Region I, the minimum stress remains zero until plasticity begins to occur in the maximum stress curve. In Region II, a small amount of compressive stress is created as the material is displaced to its original position. This compressive stress occurs in at the maximum temperature, and therefore the material exhibits elastic properties of this higher temperature. In short, the rate by which the stress decreases with respect to the strain is equal to the elastic modulus of the peak temperature.

In Chapter 2, out-of-phase TMF testing was said to occur when the minimum temperature coincides with the maximum strain, and vice versa. At the peak strain, under the conditions, where temperature is lowest, the elastic modulus and yield strength is highest. In a zero-to-tension OP test where strain is applied at a constant rate, an assumption could be made that the rate at which stress is created continues to increase along with the yield strength. This creates the overlap in maximum stress in Figure 5.15.

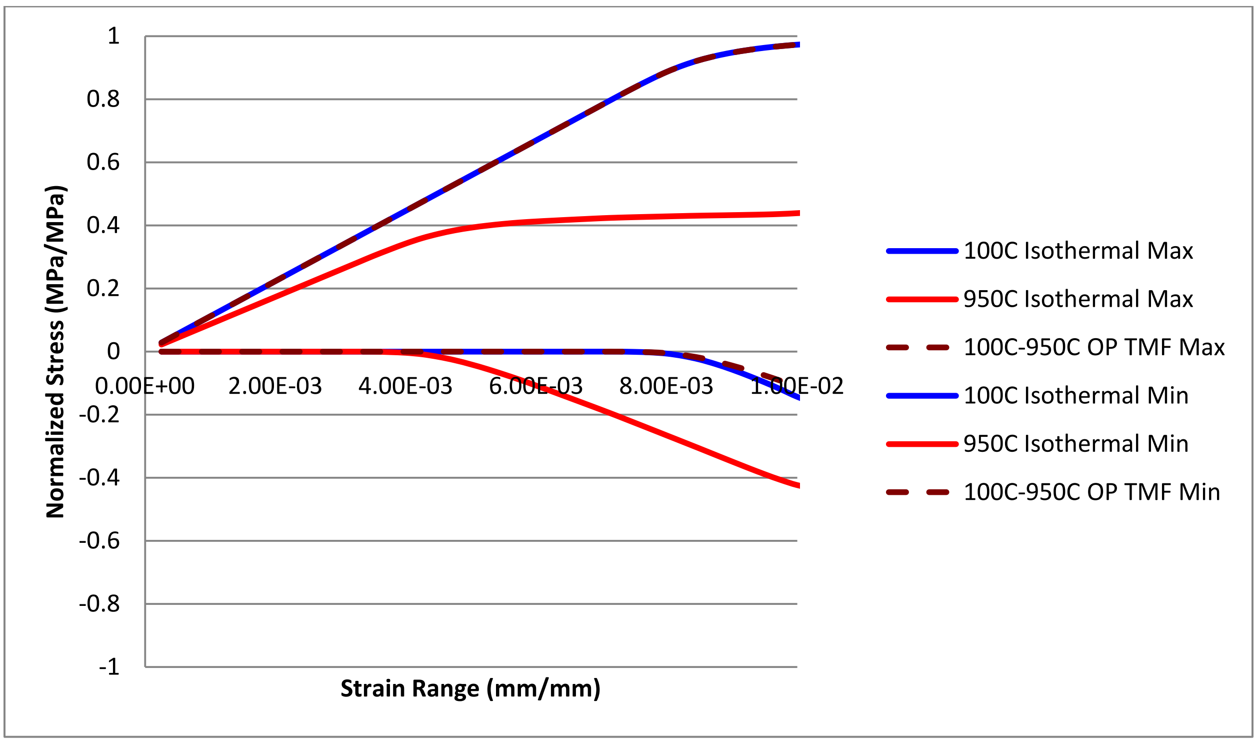


Figure 5.15: Second Cycle Minimum and Maximum Response for a Zero-to-Tension 100C-950C OP TMF Load

5.4 Variation in Strain Ratio

The material model used in this study contains properties that display tension and compression symmetry; therefore, the variation in response from a zero-to-tension IP test to a zero-to-compression OP test is identical to that of a zero-to-tension IP test to a zero-to-tension OP test. The only strain ratio must be assessed is the completely reversible case. Figure 5.16 plots data from a completely reversible (R=-1) test with comparable conditions to Figure 5.4.

The effect of the completely reversible load history on the maximum-minimum stress plot can be described as an elongation of the elastic region. This is due to the fact that the maximum strain in a zero-to-tension isothermal cycle is twice as large as that of the completely reversible cycle for the same strain range, as it is being split between a tensile strain and a compressive strain. The effect of this on the mathematical model in Equation [5.9] is the when determining the maximum stress, the elastic modulus used in Ramberg-Osgood is half of the elastic modulus of the peak isothermal temperature. The effective K and n values, as well as the compensation for stress relaxation, remain the same.

The minimum stress follows a similar trend in stress ranges before plasticity begins to develop. The response in this region can be determined using half of the elastic modulus of the minimum temperature. The divergence of this trend starts when yielding occurs in the tensile region where the maximum stress is located. Beginning from this strain range, a rapid and linear decent in minimum stress is observed, as seen in Figure 5.16. The cause can be found using the hysteresis loop of a 0.01 mm/mm strain range, completely reversible conditions of the second cycle in Figure 5.17. The buildup of inelastic response in the tensile region shifts the curve in such a way that a larger portion of the strain is experienced as a compressive stress, lowering the minimum. To account for this, the minimum stress can be estimated by making the inelastic response at the peak temperature relative to the lower temperature, and joining it with the elastic response. Mathematically, this is modeled as

$$\sigma_{\min} = -\Delta\varepsilon \cdot 0.5E_{\text{iso,min}} - \left(\frac{\Delta\varepsilon \cdot 0.5E_{iso,\max} - \sigma_{\max}}{0.5E_{iso,\max}} \right) \cdot 0.5E_{iso,\min} \qquad [5.11]$$

which can be simplified to form

$$\sigma_{\min} = -\left(\Delta\varepsilon - \frac{\sigma_{\max}}{E_{iso,\max}} \right) \cdot E_{iso,\min} \qquad [5.12]$$

This mathematical expression proves to be very accurate, as it is only off by a maximum of 0.27% from simulated results in the case analyzed above.

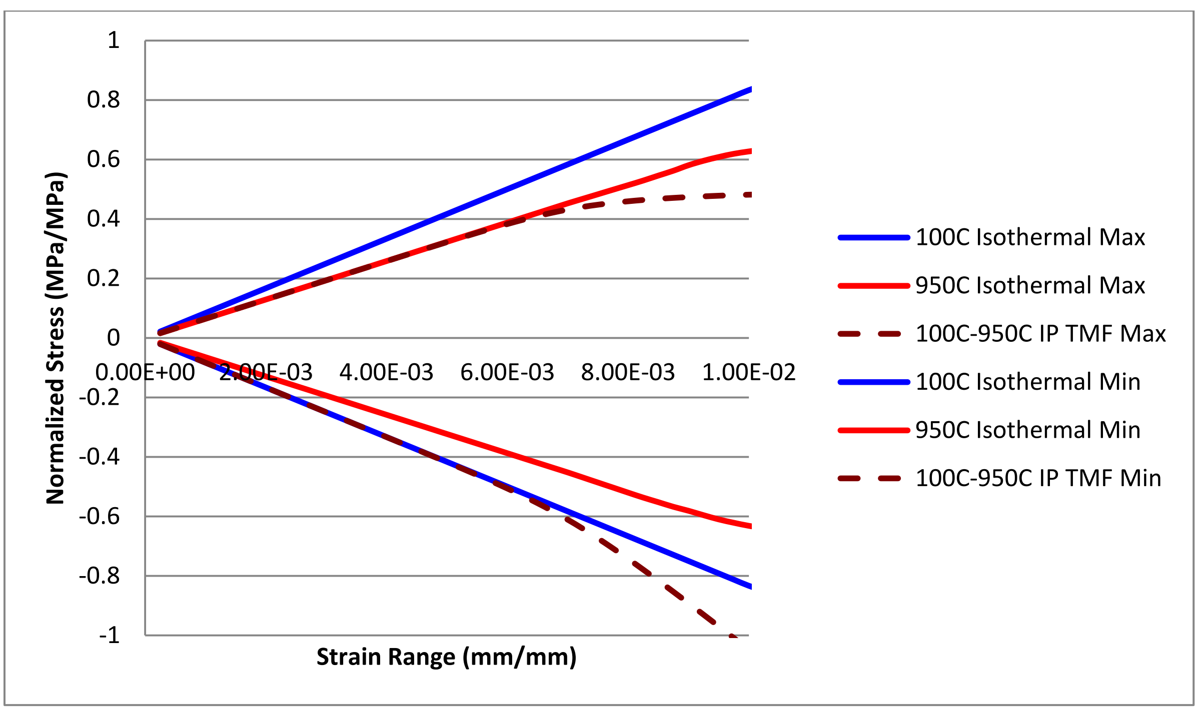


Figure 5.16: Second Cycle Minimum and Maximum Response for a Completely Reversible 100C-950C IP TMF Load

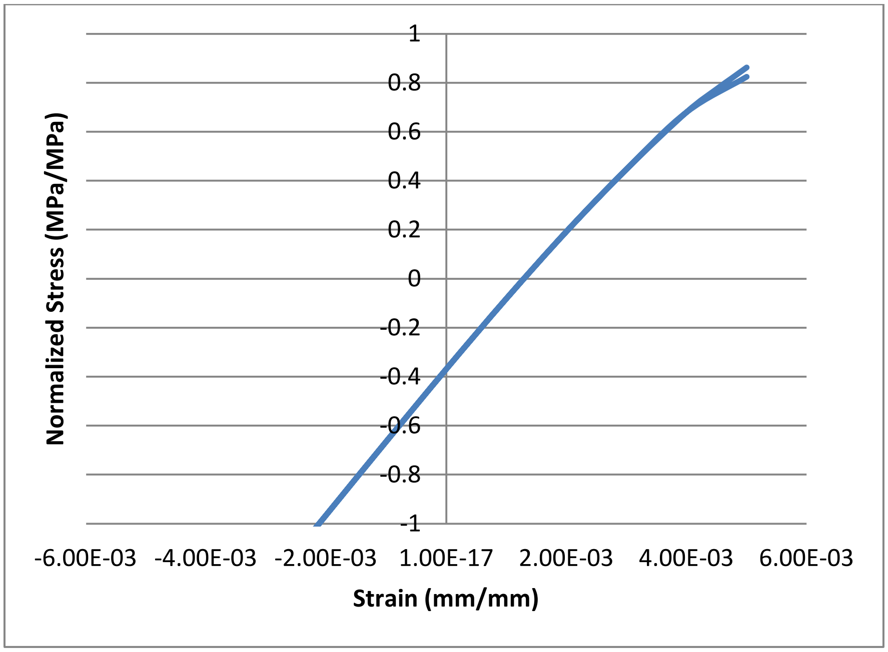


Figure 5.17: Second Cycle Hysteresis Loop for a Completely Reversible 100C-950C IP TMF Load with a Strain Range of 0.01 mm/mm

5.5 Variation in Hold Time

As can be seen in Figure 5.18, the addition a hold time creates a response that is vastly different in shape than that of the no-hold case seen in Figure 5.4. However, this variation follows many of the same trends observed in the reference case, including the estimation of the minimum stress using the elastic modulus at the lower temperature starting from the yield strain range. The primary difference occurs in the maximum stress, which follows the maximum temperature isothermal case. The isothermal and non-isothermal cases begin to diverge when the minimum stress of the isothermal condition exceeds the compressive yield strength of the material. Since the non-isothermal response has elastic modulus and yield conditions similar to the minimum temperature, compressive yielding does not occur until a larger strain range is applied. This creates the continuation of the maximum stress curve for non-isothermal conditions. Stress ranges where the material yields in the minimum strain exceed the focus of research. Therefore it can be said that the IP TMF response with a hold time can be approximated using the isothermal condition at the maximum temperature before plastic deformation has occurred in the minimum stress, and applying it throughout each strain range.

Mathematically, one could use Ramberg-Osgood with constants associated with the peak temperature to create the initial response, and use stress relaxation to account for the decrease in stress due to the hold time directly into the K constant. It should be noted that if an OP load is applied, the response is identical to the no-hold variant. The reason for this is that the hold time is always applied to the maximum temperature. As this temperature occurs at locations where stress is at a minimum, little creep deformation occurs. This is shown in Figure 5.19. Combining these observations, it is apparent that creep is the driving factor in IP TMF response containing a hold time.

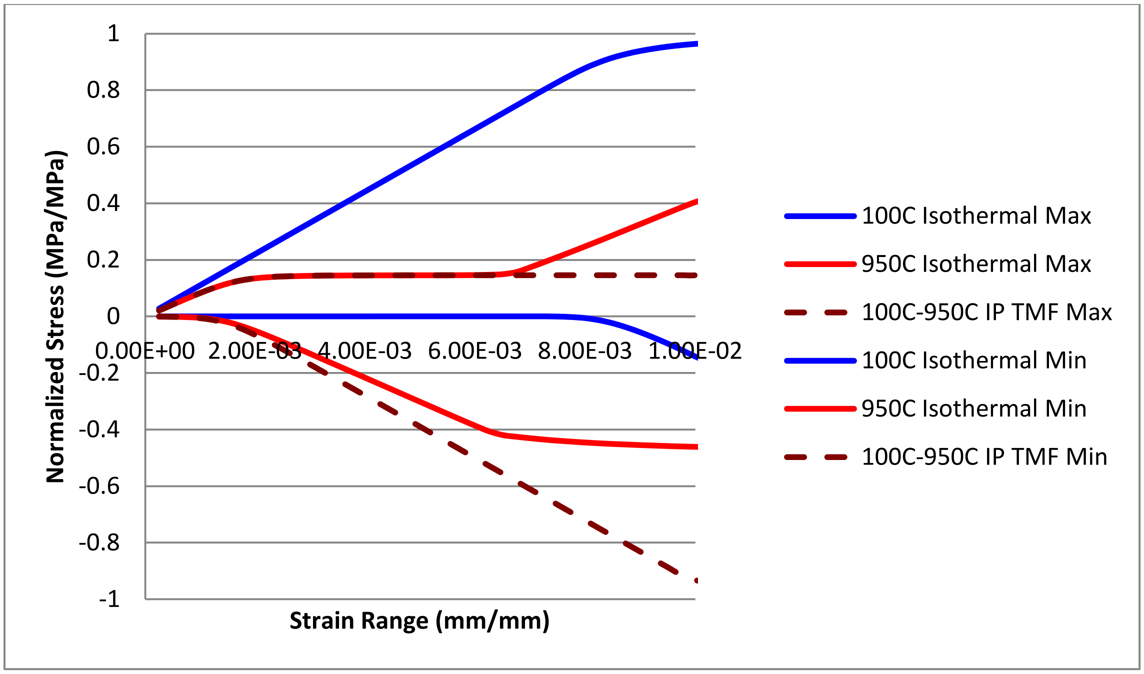


Figure 5.18: Second Cycle Minimum and Maximum Response for a Zero-to-Tension 100C-950C IP TMF Load with a 20 hr Hold Time

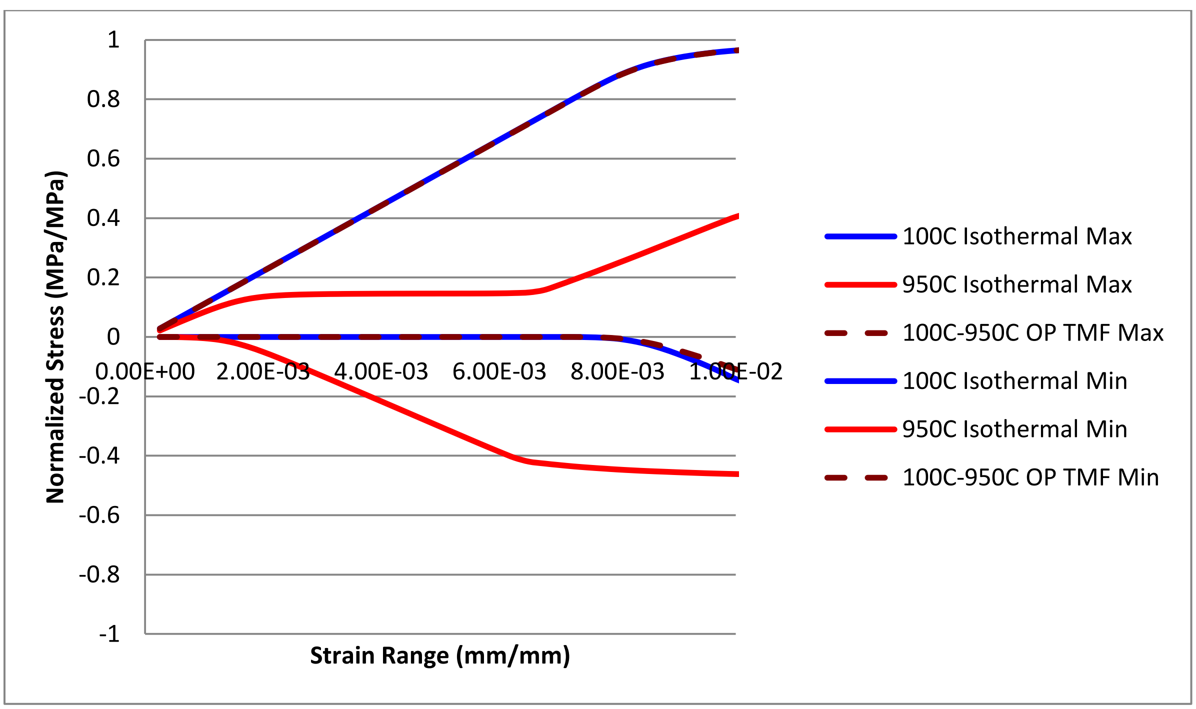


Figure 5.19: Second Cycle Minimum and Maximum Response for a Zero-to-Tension 100C-950C OP TMF Load with a 20 hr Hold Time

6. Hysteresis (TMF) Prediction Using Isothermal Results

The mathematical models developed in the previous chapter can be used to find the maximum stress and minimum stress for each strain range and cycle for load conditions that are both in-phase and out-of-phase. Estimations can be made to predict responses that also include a hold time, or vary in strain ratio. The maximum and minimum values can then be used to determine the mean stress, stress amplitude, and stress range, which are essential values when analyzing TMF data and in the application of lifing models.

These observations and equations can be combined to into several primary cases. In each of these cases, the same homologous modulus, *B*, is created from the ratio of isothermal elastic modulii from the maximum and minimum temperature of the TMF cycle. To reiterate,

$$B = \frac{E_{iso,\max}}{E_{iso,\min}} \qquad [6.1]$$

In IP zero-to-tension loads and OP zero-to-compression loads with no hold time, the maximum stress can be estimated using

$$\Delta\varepsilon = \frac{\sigma_{\max}}{E_{iso,\max}} + \left(\frac{\sigma_{\max}}{B \cdot K'_{iso,\max} - \sigma_{relaxed}} \right)^{\frac{1}{\left(B \cdot n'_{iso,\max}\right)}} \qquad [6.2]$$

where $\sigma_{relaxed}$ is the total stress relaxation up to the desired cycle calculated from Norton's power law for creep at the maximum temperature in Equation [5.5]. $K'_{iso,max}$ and $n'_{iso,max}$ are the Ramberg-Osgood constants for an isothermal load at the peak temperature. The minimum stress can be estimated using

$$\sigma_{\min} = -E_{iso,\min}\left(\frac{\sigma_{\max}}{B\cdot K'_{iso,\max} - \sigma_{relaxed}}\right)^{\frac{1}{\left(B\cdot n'_{iso,\max}\right)}} \quad [6.3]$$

where the minimum stress has a value of zero until yielding begins in the maximum stress of the TMF response. When yielding occurs, the minimum stress can be calculated from the strain range and the isothermal elastic modulus of the minimum temperature. In OP zero-to tension loads and IP zero-to compression loads with no hold, the maximum stress is identical to the isothermal response at the minimum temperature, or

$$\Delta\varepsilon = \frac{\sigma_{\max}}{E_{iso,\min}} + \left(\frac{\sigma_{\max}}{K'_{iso,\min}}\right)^{\frac{1}{n'_{iso,\min}}} \quad [6.4]$$

and the minimum stress is zero until yielding occurs in the maximum stress, and afterwards is calculated using the elastic modulus of the maximum temperature, such that

$$\sigma_{\min} = -E_{iso,\max}\left(\frac{\sigma_{\max}}{K'_{iso,\min}}\right)^{\frac{1}{n'_{iso,\min}}} \quad [6.5]$$

Maximum stress in a completely reversible load cases can be estimated using

$$\Delta\varepsilon = \frac{\sigma_{\max}}{0.5E_{iso,\max}} + \left(\frac{\sigma_{\max}}{B\cdot K'_{iso,\max} - \sigma_{relaxed}}\right)^{\frac{1}{B\cdot n'_{iso,\max}}} \quad [6.6]$$

and the minimum stress can be estimated using

$$\sigma_{\min} = -\left(\Delta\varepsilon - \frac{\sigma_{\max}}{E_{iso,\max}}\right)\cdot E_{iso,\min} \quad [6.7]$$

Load conditions that include a hold time can also be estimated. For an in-phase load, the maximum is estimated using the Ramberg-Osgood constants of the maximum temperature and the total stress relaxation of the peak isothermal response to form

$$\Delta\varepsilon = \frac{\sigma_{\max}}{E_{iso,\max}} + \left(\frac{\sigma_{\max}}{K'_{iso,\max} - \sigma_{relaxed}}\right)^{\frac{1}{n'_{iso,\max}}} \tag{6.8}$$

and the minimum stress is zero before yielding occurs in the maximum stress, and is then calculated from the isothermal elastic modulus at the minimum temperature such that

$$\sigma_{\min} = -E_{iso,\min}\left(\frac{\sigma_{\max}}{K'_{iso,\max} - \sigma_{relaxed}}\right)^{\frac{1}{\left(n'_{iso,\max}\right)}} \tag{6.9}$$

If the response is out-of-phase, the maximum stress can be estimated using the Ramberg-Osgood constants at the minimum temperature with

$$\Delta\varepsilon = \frac{\sigma_{\max}}{E_{iso,\min}} + \left(\frac{\sigma_{\max}}{K'_{iso,\min}}\right)^{\frac{1}{n'_{iso,\min}}} \tag{6.10}$$

Minimum stress for the out-of-phase response can be estimated in a similar manner to the in-phase response, where

$$\sigma_{\min} = -E_{iso,\max}\left(\frac{\sigma_{\max}}{K'_{iso,\min}}\right)^{\frac{1}{n'_{iso,\min}}} \tag{6.11}$$

Therefore, by using these estimation functions the upper and lower bounds of the stress response can be determined using the constants associated with the isothermal counterparts. These functions were created by comparison of the isothermal and non-isothermal responses in a maximum-minimum stress to strain range plot. The observations outlined in Chapter 5 hold true for combinations of the listed variations, though the most general of which are mathematically modeled above. Variation in grain orientation has also been tested. Due to the fact that the stress in the loading direction was analyzed in each case, the response was essentially the same as using a different set of isothermal constants tuned to that orientation. An in-depth analysis to relate the transverse and 45° orientation remains a topic of future study, though the majority of the tools required to conduct these simulations is already coded.

7. Notch TMF Results

The observations and resulting estimation functions described in previous sections are created as modifications to Ramberg-Osgood plasticity. The benefits of using this plasticity model as the basis for TMF prediction is the model has been adapted to a vast number of readily available applications and supporting equations. To test for the high level of versatility the TMF estimation functions can potentially exhibit, the case of a V-notched specimen is used.

The underlying assumption when using Neuber's rule is that the notch response is limited to small-scale yielding. This implies that the remote stress used in Equation [2.5] must be purely elastic. In Chapter 5, it was observed that in the case of a displacement-controlled test, where the strain range is contained in Region I and only elasticity is present; the stress response under IP TMF conditions is identical to that of isothermal conditions at the peak temperature. This observation holds for the remote stress in the grip. That is to say,

$$\frac{K_t^2 \Delta S_{n,\mathrm{iso,max}}^2}{E} = \frac{K_t^2 \Delta S_{n,\mathrm{TMF}}^2}{E} \qquad [7.1]$$

where the values for the elastic modulus and the stress concentration factor are equal and $\Delta S_{n,iso,max}$ is the nominal stress under isothermal conditions and $\Delta S_{n,TMF}$ is the nominal stress under non-isothermal conditions. The hysteresis data of the grip under isothermal and non-isothermal conditions are plotted in Figure 7.1.

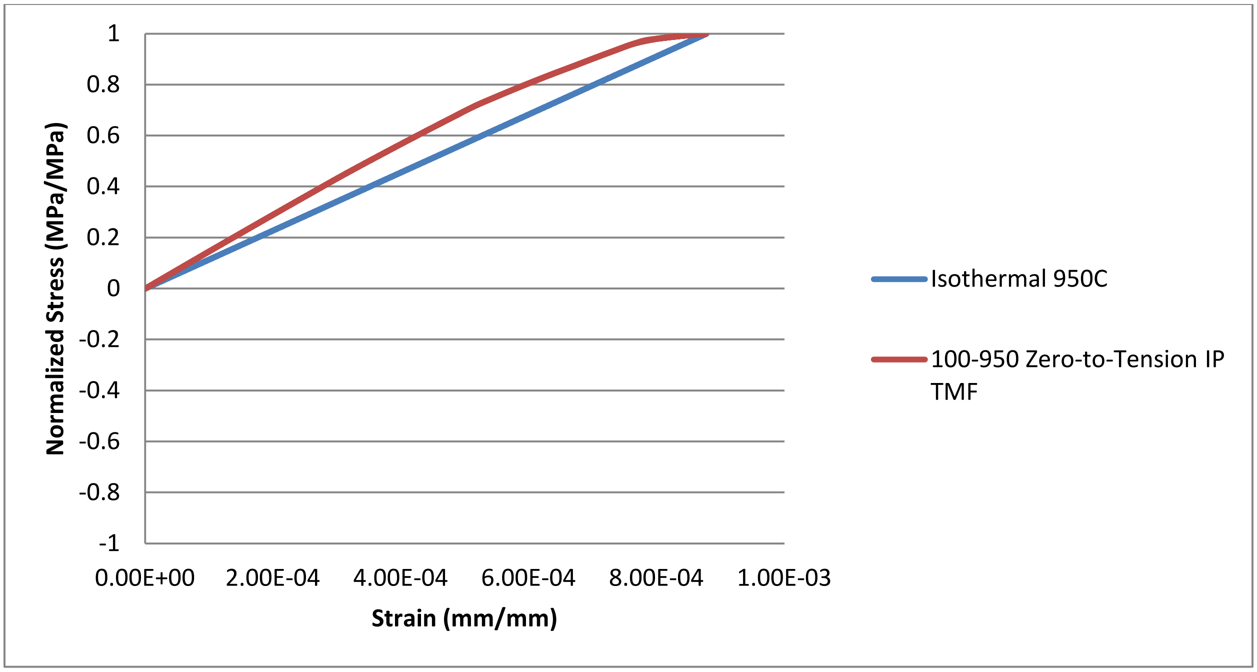


Figure 7.1: Hysteresis Plots of the Second Cycle Remote Zero-to-Tension Response Under 950°C Isothermal and 100°C-950°C IP TMF Loading

Thus, to prove Neuber's rule holds for TMF, the relation

$$\Delta\sigma_{iso,\max}\Delta\varepsilon_{iso,\max} = \Delta\sigma_{TMF}\Delta\varepsilon_{TMF} \qquad [7.2]$$

must be true, where $\Delta\sigma_{iso,max}$ and $\Delta\varepsilon_{iso,max}$ are the local stress range and local strain range at the notch tip under isothermal loading at the maximum temperature, and $\Delta\sigma_{TMF}$ and $\Delta\varepsilon_{TMF}$ are the local stress range and local strain range at the notch tip under TMF loading. Figure 7.2 contains a hysteresis plot of the isothermal response at the peak temperature and the TMF response in a completely reversed loading. The displacement applied to the remote location is chosen so that plasticity begins to develop in the notch for the isothermal case, but not for the TMF case. In this instance, Equation [7.2] does not hold true, and we can conclude that Neuber's rule cannot be directly applied to TMF without modification.

It should be noted that under closer inspection of Figure 7.1, response at the notch tip contains a dislocation where a sudden jump from a tensile to compressive loading occurs mid-cycle. This response was typical in the simulations conducted in this study, as a common drawback to displacement-controlled loading at the remote location is a ratcheting effect. This is also shown in Figure 7.3.

Though this makes a quantitative study of notched TMF impossible, observations of the response can still be made. One such observation is that despite the ratcheting, unaffected regions in the TMF response continue to display a Ramberg-Osgood trend similar to that of the un-notched simulation results. Another observation can be made by studying the peak stress between cycles in Figure 7.3. These peak stresses decrease in magnitude and in rate of decent. If fact, numerical results show that this decrease is not only a power law, but that it is nearly identical to drop in stress observed in un-notched TMF results. Therefore, we can conclude that the drop between cycles is unaffected by the presence of stress raiser, or geometric factor if the temperature is uniform about the entire structure.

A final, non-isothermal, non-local approach is not created in this study. However, the categorization of thermomechanical fatigue in un-notched structures and the observations made in this chapter provide much needed insight on the subject.

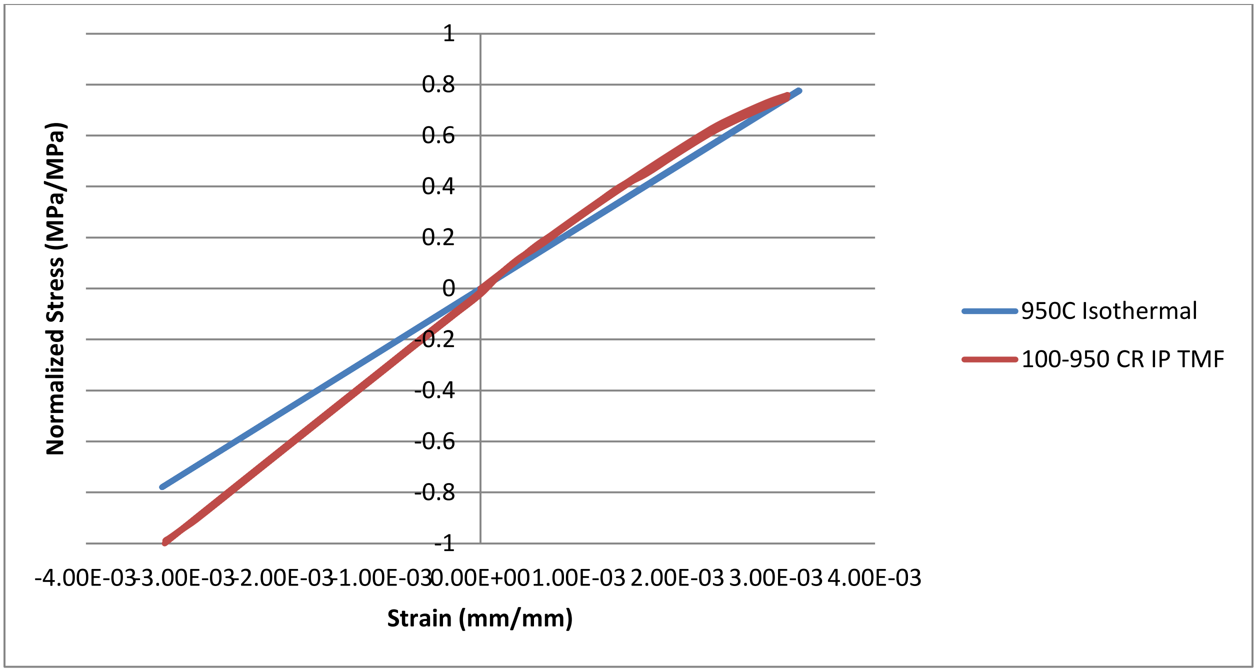


Figure 7.2: Hysteresis of the Second Cycle Local CR Response, 950°C Isothermal and 100°C-950°C IP TMF

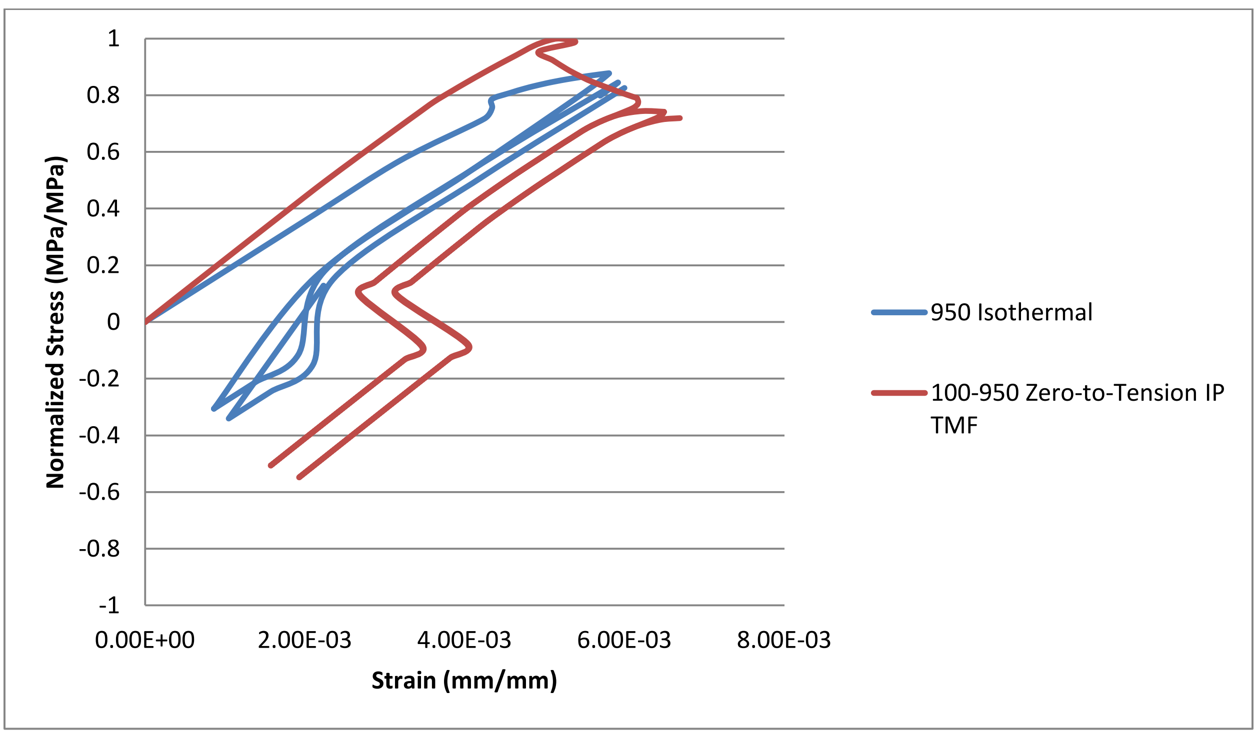


Figure 7.3: Hysteresis of the Second Cycle Local Zero-to-Tension Response, 950°C Isothermal and 100°C-950°C IP TMF

8. Conclusions

Using a single-element FE model, 7200 combinations of isothermal and non-isothermal load histories with varying temperatures, strain ranges, and other conditions have been applied. These simulation results are used to generate plots of the maximum and minimum stress versus the strain range, as well as hysteresis loops. By comparing each non-isothermal response with that of the isothermal case at the maximum and minimum temperature, consistent trends can be observed. Analysis of these observations show that in most cases, the maximum and minimum stress of a material subjected to thermomechanical fatigue can be directly compared to that of an isothermal case. Those that cannot be directly related can be estimated using the homologous modulus and the Ramberg-Osgood relationship. This modification factor is created using the ratio of the elastic modulus of the maximum temperature to that of the minimum temperature.

The simplicity of the modification to allow for the prediction of thermomechanical fatigue, as well as the consistency in form with previous elastic-plastic models, makes application a readily available avenue. This is attempted in the notched FE model. Traditional isothermal analysis of a specimen with a v-shaped notch is conducted using Neuber's rule, or an evolution of the relationship.

The culmination of these estimation methods would be the ability to estimate the maximum and minimum local stress at a notch tip given a remote stress at a location away from the stress field using isothermal material properties. Although this was not fully realized, critical observations have been made. Results demonstrate that the general form of the hysteresis response remains true to un-notched analysis, documented shakedown approaches are not directly applicable in TMF, and that the drop in local notch stress between cycles is equivalent to the relaxed stress due to creep. We can conclude that further analysis of this topic is necessary, and it is likely that the resulting equations will be similar to the un-notched case.

9. Future Work

Much has been learned over the course of this study, but due to time constraints, many topics have yet to be thoroughly examined. The first and foremost of which, is the reason why the homologous modulus created from the isothermal elastic modulii works. The hysteresis loop for several strain ranges suggest that this is related to the stresses created from the larger elastic modulus in the lower temperature carried over as the temperature increases and the yield strength decreases. Although this may be the case, analysis of the microstructure or physical tests designed to examine this particular response would shed some insight.

Though the material model used in simulations throughout this study have been created using actual data, a small set of dedicated experiments could be conducted to further validate the resulting estimation techniques. Among these would be IP and OP zero-to-tension tests both with and without a hold time, and a peak temperature of 750°C, 850°C and 950°C at a strain range of 0.0025 mm/mm, 0.0075 mm/mm, and 0.01 mm/mm. Completely reversible tests with the same strain range and a peak temperature of 950°C would also prove useful. This study analyzed results from a single material. In order to truly validate the model, similar tests or perhaps another FE study must be conducted for a different material.

The scope set at the beginning of this research included variation in orientation. The observations are based on isothermal properties at the given orientation. A topic of later research will be to allow for estimation of maximum and minimum stress for any orientation using the isothermal properties in the longitudinal direction. The finite element code produced for this study already includes material orientation, so the tools are already there. All that remains is to review past literature associated with orientation changes, and attempt to adapt these ideas with the TMF observations and tools used in this study.

Additional analysis of structures containing a stress concentration factor must also be conducted. Preliminary results from this study provide insight, though significant changes to the FE code are needed. Among which is a method to control the test using strain at the notch. This would cut down on ratcheting effects, as well as provide an alternate method to compare isothermal and non-isothermal responses. For now, the loading is coded in such a way that the displacement is controlled at the remote location, meaning that remote strain will be the same. Although this may help in determining the applicability of Neuber's rule, it makes analysis of TMF difficult.

10. References

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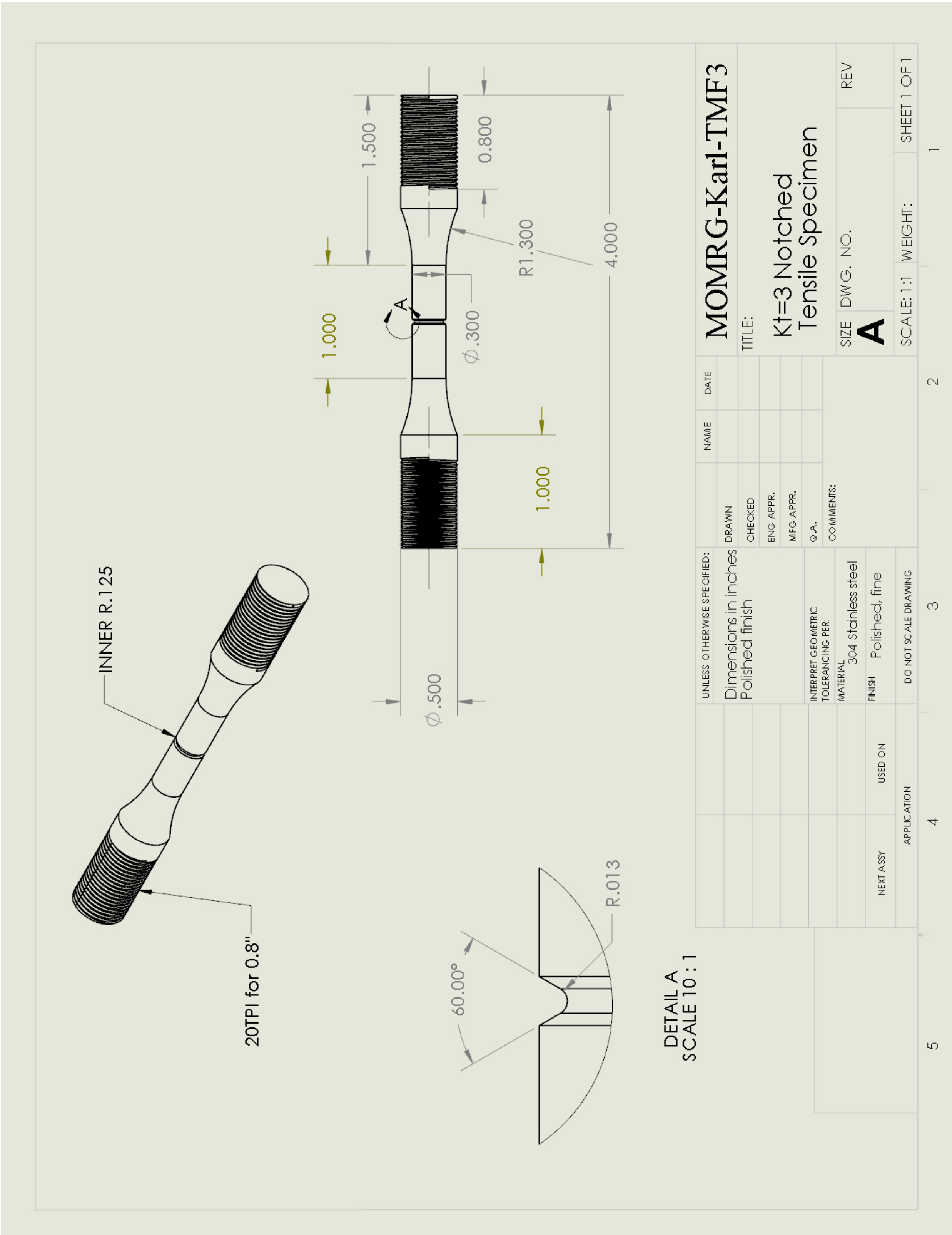
Appendix A: Reference Document for Specimen Dimensions [Karl, 2013]



MOMRG-Karl-TMF3
TITLE:
Kt=3 Notched Tensile Specimen
SIZE
A
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED:
Dimensions in inches
Polished finish
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
304 Stainless steel
FINISH
Polished, fine
DO NOT SCALE DRAWING
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NAME
DATE
NEXT ASSY
USED ON
APPLICATION
INNER R.125
20TPI for 0.8"
DETAIL A
SCALE 10 : 1
60.00°
R.013
1.500
0.800
R1.300
4.000
1.000
1.000
⌀.300
⌀.500
A

Appendix B: Un-notched Code

```
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
! ANSYS Finite Element Modeling (FEM) Simulation of Fatigue
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
! Author: Various (Bouchenot, Keller, Mutter)
! ver. 0.2
! Date: 6/10/13
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
Finish
/Clear
/Prep7
Cl='Cl1'    ! Class: 1-Single Element Parametric Simulation
St='St1'    ! Study: 1-Isothermal Fatigue in L-orientation
Ph='Ph1a'   ! Phase: 1a
!       Strain Rate:   0.01s^-1 or 0.01/300S^-1
!       Temperatures:  20 to 1050C
!       Strain Ranges: 0% to 3% (by 0.1%)
!       M Ratio:  -1,0,or 1 (Note: M = A^-1)
!
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!
! Description: A Solid185 Element is subjected to strain-controlled
! fatigue in units of (m, N, MPa). Results are collected in a text file
! for later post-processing.
!
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!


!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
! Parametric File Setup
!
! Thermal Cycling
isotherm=1.0            ! 0=Yes, 1=No
SINGLEHOLD=1                    ! 0=two holds (normal), 1= single hold at the max temperature
holdnumber_ini=1        ! For use when singlehold=1
holdnumber_inc=1        ! 1=0hr, 2=5hr, 3=20hr
holdnumber_fin=3
tmt_ini=100.0           ! Initial Min temperature [degrees C]
tmt_inc=850.0           ! Increment Min temperature [degrees C]
tmt_fin=950.0           ! Final Min temperature [degrees C]
tmc_ini=100.0           ! Initial Max temperature [degrees C]
tmc_inc=850.0                   ! Increment Max temperature [degrees C]
tmc_fin=950.0                   ! Final Max temperature [degrees C]
!
! Mechanical Cycling
sr_ini=0.0001           ! Initial Strain range [mm/mm]
sr_inc=0.00025                  ! Increment Strain range  [mm/mm]
```

```
sr_fin=0.012            ! Final Strain range [mm/mm]
mrat_ini=1              ! -1=ZtC, 0=CR, 1=ZtT, 2= SR of 0.05
mrat_inc=-1
mrat_fin=-1
!
! Material Orientation
ang_ini=90.0      ! 90 is L-oriented 0 is T-oriented
ang_inc=-45.0
ang_fin=0.0
!
!Configuring the Cleaned Results File
*CFOPEN, C:\Simulations\FEA_CLEANED_%st%_%cl%_%ph%,data,
LABEL1='    sr            tmca'
LABEL2='           tmt           re'
LABEL3='        strain_rate'
LABEL4='      total_cycles       ang'
LABEL5='        hold_time      M'
LABEL6='AXTEMP'
LABEL7='        MINTEMP     MAXE'
LABEL8='STRAIN       MINESTRAIN'
LABEL9='      MAXPSTRAIN      MINPS'
LABEL10='TRAIN      MAXCSTRAIN'
LABEL11='      MINCSTRAIN       MAXST'
LABEL12='RESS      MINSTRESS'

*VWRITE, LABEL1, LABEL2, LABEL3,
LABEL4,LABEL5,LABEL6,LABEL7,LABEL8,LABEL9,LABEL10,LABEL11,LABEL12
%C%C%C%C%C%C%C%C%C%C%C%C

!Configuring the Second Cleaned Results File
*CFOPEN, C:\Simulations\FEA_CLEANED2_%st%_%cl%_%ph%,data,
LABEL1='    sr            tmt'
LABEL2='          tmca           re'
LABEL3='        strain_rate'
LABEL4='      total_cycles       ang'
LABEL5='        hold_time      E'
LABEL6='xt_Initial'
LABEL7='    Relax_Stress_1  Relax'
LABEL8='_Stress_2  Min_Stress_1'
LABEL9='     Max_Stress_1   Min Stress_2'
LABEL10='    Max_Stress_2 P_Str'
LABEL11='ain_Range_1  P_Strain_Range_2'

*VWRITE, LABEL1, LABEL2, LABEL3,
LABEL4,LABEL5,LABEL6,LABEL7,LABEL8,LABEL9,LABEL10,LABEL11
%C%C%C%C%C%C%C%C%C%C%C
```

```
/OUTPUT,C:\Simulations\FEA_Junk10,txt
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!


!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
! Parametric Simulation Initiation
!
I=1
J=1
K=1
L=1
M=1
*DO,tmc,tmc_ini,tmc_fin,tmc_inc             ! Compressive temperature [degrees C]
*DO,tmt,tmt_ini,tmt_fin,tmt_inc             ! Tensile temperature [degrees C]
*DO,mrat,mrat_ini,mrat_fin,mrat_inc         ! Strain ratio [unitless]
*DO,sr,sr_ini,sr_fin,sr_inc         ! Strain range [mm/mm]
*DO,ang,ang_ini,ang_fin,ang_inc             ! Strain range [mm/mm]
*DO,holdnumber,holdnumber_ini,holdnumber_fin,holdnumber_inc !hold time for single hold

PARSAV,,C:\Simulations\FEA_Parameters1,txt
*IF,I,GT,1,THEN
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!


!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!
! File Naming Convention
Finish
/clear
/PREP7
PARRES,,C:\Simulations\FEA_Parameters1,txt
*ENDIF
Finish
/FILNAME, C1-S1-Ph1a
/title, C1-S1-Ph1a Isothermal Fatigue Simulation
/prep7
/OUTPUT, C:\Simulations\FEA_Junk1,txt,,
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!


!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!
! Dwells
!
*IF, holdnumber, EQ, 1, THEN
```

```
holdtime=1.02e-2/3600
*ENDIF

*IF, holdnumber, EQ, 2, THEN
holdtime=5
*ENDIF

*IF, holdnumber, EQ, 3, THEN
holdtime=20
*ENDIF
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!


!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!
! Define the specimen dimensions
!
side_length=1.00   ! in units of mm
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!


!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!
! Define the nodes
! Total of 8 Nodes
N, 1 ,0,0,0                                        ! Node,number,xcord,ycord,zcord
N, 2 ,side_length,0,0
N, 3 ,side_length,side_length,0
N, 4 ,0,side_length,0
N, 5 ,0,0,side_length
N, 6 ,1,0,side_length
N, 7 ,side_length,side_length,side_length
N, 8 ,0,side_length,side_length
!
! Create Node Groups
!
! All Nodes - NDALL
NSEL, S , node , , 1 , 8 , 1
CM, NDALL , NODE
!
! Bottom Nodes - BOTTOM
NSEL, S , node , , 1 , 4 , 1
CM, BOTTOM , NODE
!
! Top Nodes - TOP
NSEL, S , node , , 5 , 8 , 1
```

```
CM, TOP , NODE
!
! Clear Selected Nodes
NSEL, ALL
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!


!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!
! Define a local system to transform material properties into desired orientation
local,11,0,0,0,0,0,0,ang,,        ! use this one to rotate in the transverse plane..
!local,11,0,0,0,0,0,0,ang,0,,      ! ...or this one to rotate from T to L
ESYS,11                           ! the local system is selected for all defined elements
!
! Define the elements
ET, 1 , Solid185 , 0
!
! Assign elements to nodes
E, 1 , 2 , 3 , 4 , 5 , 6 , 7 , 8
!
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!


!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

! Define the material

! Material model removed for publication
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!


!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!
! Create Boundary Conditions
!
! Left Boundary
D, 1 , UX , 0          ! Fixed X displacement on LEFT nodes
D, 4 , UX , 0          ! Fixed X displacement on LEFT nodes
D, 5 , UX , 0          ! Fixed X displacement on LEFT nodes
D, 8 , UX , 0          ! Fixed X displacement on LEFT nodes
!
! Bottom Boundary
D, BOTTOM , UZ , 0 ! Fixed Z displacement on BOTTOM nodes
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
```

```
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!
! Define Fatigue Cycling Parameters:
!
! Mechanical Loading
strain_range = sr                ! Difference in Max and Min strains [mm/mm]
strain_rate = 0.001              ! Strain rate [mm/mm/s or %/min]
tol=0.0001
re=(mrat-1+tol)/(mrat+1+tol) ! Strain ratio (0=ZtT,-1=CR,-900=ZtC)
strain_ratio=re
*IF, mrat, EQ, 2, THEN
strain_ratio=0.05
*ENDIF
tens_hold = 18                   ! Tension hold, disable if previously defined [hr]
comp_hold = 1.02e-2/3600         ! Compression hold, disable if previously defined [hr]
first_hold = 1.01e-2/3600        ! First hold [hr] ex:5000 hr hold
displ_range = strain_range*side_length          ! Displacement [mm]
displ_max = displ_range/(1.0-strain_ratio)   ! Displacement [mm]
displ_min = displ_max-displ_range            ! Displacement [mm]
displ_mean = 0.5*(displ_max+displ_min)          ! Displacement [mm]
strain_rate_hr = strain_rate*3600.0          ! Strain rate [mm/mm/hr]
half_cycle = strain_range/strain_rate_hr/2.0 ! Half cycle [hr]
full_cycle = 2.0*half_cycle                  ! Full cycle [hr]

! Cycle Stepping and Ramping Time

num_cycles = 3
tot_load_steps=num_cycles*4+2
load_init_time = 1.0E-2/3600.0                  ! Initial Load Time [hr]
load_mini_time = 1.0E-4/3600.0                  ! Minimum Deltim step time [hr]
load_mini_dwell_time = 1.0E-4/3600.0            ! Minimum Deltim step time [hr]
load_maxi_time = 1.0E-1/3600.0                  ! Maximum Deltim step time [hr]
load_maxi_dwell_time = 300                   ! Maximum Deltim step time [hr]
load_ramp_time = 1.0E-10/3600.0                 ! Ramp time used in Deltim [hr]
data_freq = 1.0                                 ! Frequency of data capture
!
! Temperature Cycling
tmca=tmc*isotherm+(1-isotherm)*tmt
max_temp=0.5*(tmt+tmca+abs(tmt-tmca))
min_temp=0.5*(tmt+tmca-abs(tmt-tmca))
temp_range=abs(tmt-tmca)
!temp_rate=temp_range/full_cycle
!
*IF, tmt, NE, tmca, THEN                     !temp controlled strain rate for TMF
temp_rate = 3                                !3 degress/second for TMF
temp_rate_hr = temp_rate*3600.0
```

```
half_cycle = temp_range/temp_rate_hr/2.0   ! Half cycle [hr]
full_cycle = 2.0*half_cycle                ! Full cycle [hr]
*ENDIF

load_init_time = half_cycle/20.0           ! Initial Load Time [hr]
load_mini_time = half_cycle/200.0          ! Minimum Deltim step time [hr]
load_maxi_time = half_cycle/5.0                  ! Maximum Deltim step time [hr]

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!


!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!
! Assign the Peak-Valley-Period Values (based on strain ratio and phasing)
!
! Cycling rules:
!       Rule #2: If CR and compression hold exceeds tensile hold, then go to compression first
!     Rule #3: If zero-to-compression, proceed to minimum displacement first
!     Rule #4: If zero-to-tension, proceed to maximum displacement first
!     Rule #5: Initial portion of the cycle goes from zero-displacement and mean temp
!
!
peak_displ=displ_max
valley_displ=displ_min
peak_hold=tens_hold
valley_hold=comp_hold
mean_temp=0.5*(tmt+tmca)
temp_init=mean_temp
peak_temp=tmt
valley_temp=tmca
!
!
*IF, SINGLEHOLD, EQ, 0, THEN
*IF,mrat,eq,0,and,comp_hold,gt,tens_hold,THEN ! See Rule #2
peak_displ=displ_min
valley_displ=displ_max
*ENDIF
*ENDIF
!
*IF,mrat,eq,-1,THEN ! See Rule #3 (only in Z-to-C case)
peak_displ=displ_min
valley_displ=displ_max
peak_hold=comp_hold
valley_hold=tens_hold
half_cycle=half_cycle*2
peak_temp=tmca
```

```
valley_temp=tmt
temp_init=tmt
*ENDIF
!
*IF,mrat,eq,1,THEN   ! See Rule #4 (only in Z-to-T case)
peak_displ=displ_max
valley_displ=displ_min
peak_hold=tens_hold
valley_hold=comp_hold
half_cycle=half_cycle*2
peak_temp=tmt
valley_temp=tmca
temp_init=tmca
*ENDIF
!
*IF,mrat,eq,-1,THEN ! See Rule #5
init_period_hr=half_cycle*peak_displ/displ_range
displ_init=0
*ENDIF
!
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!


!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

! For hold only at max temp
*IF, SINGLEHOLD, EQ, 1, THEN
*IF, peak_temp, GE, valley_temp, THEN
peak_hold=holdtime
valley_hold=1.01e-2/3600
*ENDIF

*IF, peak_temp, LT, valley_temp, THEN
peak_hold=1.01e-2/3600
valley_hold=holdtime
*ENDIF

!*IF, peak_temp, EQ, valley_temp, THEN
!peak_hold=holdtime
!valley_hold=holdtime
!*ENDIF

*IF,mrat,eq,0,and,valley_hold,gt,peak_hold,THEN ! See Rule #2
peak_displ=displ_min
valley_displ=displ_max
*ENDIF
```

```
*ENDIF

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!


!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

! Fixing the substep times

load_init_dwell_time_peak = 1.0E-2/3600.0
load_init_dwell_time_valley = 1.0E-2/3600.0
load_init_dwell_time_first = 1.0E-2/3600.0

*IF, first_hold, GT, 2.0E-2/3600, THEN
load_init_dwell_time_first = first_hold/20
*ENDIF

*IF, peak_hold, GT, 2.0E-2/3600, THEN
load_init_dwell_time_peak = peak_hold/20
*ENDIF

*IF, valley_hold, GT, 2.0E-2/3600, THEN
load_init_dwell_time_valley = valley_hold/20
*ENDIF

FINISH                  ! Finish pre-processing
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!


!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!
! Begin Initial Solution Stage
/CONFIG,NRES,500000
/NERR,5000000,5000000,,0
*DIM,LOADSUBS,ARRAY,1,tot_load_steps              ! Array for amount of substeps
/SOLU
ALLSEL

! Step 1
total_time = abs(load_ramp_time)            ! Total time [s]
Antype, trans
nropt,auto                                  ! Uses Newton-Raphson
lnsrch,auto                                 ! Auto line searching for NR
NLGEOM,auto                               ! Non-linear geometry
Solcontrol, 1                               ! Optimizes nonlinear solutions
```

```
Cnvtol,F,3
Time, total_time                          ! Time at end of step
!NSUBST,20,1000,20                        ! Specifies substeps
Deltim, load_init_time, load_mini_time, load_maxi_time    ! DELTIM, DTIME, DTMIN,
DTMAX, Carry
Autots, 1                                 ! Auto Time Stepping
D, TOP , UZ , displ_init
BF,ALL,TEMP,temp_init                          ! Nodal body force load
Outres, All, data_freq                    ! Outputs data to be read by ESOL
Crplim, 20, 1                             ! Creep Ratio
Rate, 1                                   ! Activates Creep for step
Kbc, 0                                    ! Specifies stepped or ramped load, 1=stepped
Solve
*GET, LOADSUBS(1,1),ACTIVE,0,SOLU, NCMSS

! Step 2:
total_time = abs(half_cycle)+total_time
Antype, trans
nropt,auto
lnsrch,auto
NLGEOM,auto
Solcontrol, 1
Cnvtol,F,3
Time, total_time
!NSUBST,20,1000,20
Deltim, load_init_time, load_mini_time, load_maxi_time

Autots, 1
D, TOP , UZ , peak_displ
BF,ALL,TEMP,peak_temp
Outres, All, data_freq
Crplim, 20, 1
Rate, 1
Kbc, 0
Solve
*GET, LOADSUBS(1,2),ACTIVE,0,SOLU, NCMSS

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!


!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

! Continue Solution Stage with Subsequent Cycling
total_cycles=num_cycles                              ! Number of cycles
*do,cycle,1,total_cycles,1
```

```
! Step 3:
*GET, LOADNUM,ACTIVE,0,SOLU, NCMLS
!*IF, LOADNUM, EQ, 2, THEN                    ! Activate if have first hold
!total_time = abs(first_hold) + total_time
!*ELSE
total_time = abs(peak_hold) + total_time
!*ENDIF
Antype, trans
nropt,auto
lnsrch,auto
NLGEOM,auto
Solcontrol, 1
Cnvtol,F,3
Time, total_time
!NSUBST,20,1000,20
!*IF, LOADNUM, EQ, 2, THEN
!Deltim, load_init_dwell_time_first, load_mini_dwell_time, load_maxi_dwell_time
!*ELSE
Deltim, load_init_dwell_time_peak, load_mini_dwell_time, load_maxi_dwell_time
!*ENDIF
Autots, 1
D, TOP , UZ , peak_displ
NSEL,ALL
BF,ALL,TEMP,peak_temp
Outres, All, data_freq
Crplim, 20, 1
Rate, 1
Kbc, 0
Solve
*GET, LOADSUBS(1,2+cycle*4-3),ACTIVE,0,SOLU, NCMSS

! Step 4:
total_time = abs(full_cycle) + total_time
Antype, trans
nropt,auto
lnsrch,auto
NLGEOM,auto
Solcontrol, 1
Cnvtol,F,3
Time, total_time
!NSUBST,20,1000,20
Deltim, load_init_time, load_mini_time, load_maxi_time
Autots, 1
D, TOP , UZ , valley_displ
NSEL,ALL
BF,ALL,TEMP,valley_temp
```

```
Outres, All, data_freq
Crplim, 20, 1
Rate, 1
Kbc, 0
Solve
*GET, LOADSUBS(1,2+cycle*4-2),ACTIVE,0,SOLU, NCMSS

! Step 5:
total_time = abs(valley_hold) + total_time
Antype, trans
nropt,auto
lnsrch,auto
NLGEOM,auto
Solcontrol, 1
Cnvtol,F,3
Time, total_time
!NSUBST,20,1000,20
Deltim, load_init_dwell_time_valley, load_mini_dwell_time, load_maxi_dwell_time
Autots, 1
D, TOP , UZ , valley_displ
NSEL,ALL
BF,ALL,TEMP,valley_temp
Outres, all, data_freq
Crplim, 20, 1
Rate, 1
Kbc, 0
Solve
*GET, LOADSUBS(1,2+cycle*4-1),ACTIVE,0,SOLU, NCMSS

! Step 6:
total_time = abs(full_cycle) + total_time
Antype, trans
nropt,auto
lnsrch,auto
NLGEOM,auto
Solcontrol, 1
Cnvtol,F,3
Time, total_time
!NSUBST,25,1000,20
Deltim, load_init_time, load_mini_time, load_maxi_time
Autots, 1
D, TOP , UZ , peak_displ
NSEL,ALL
BF,ALL,TEMP,peak_temp
Outres, all, data_freq
Crplim, 20, 1
```

```
Rate, 1
Kbc, 0
Solve
rescontrol,file_summary
*GET, LOADSUBS(1,2+cycle*4),ACTIVE,0,SOLU, NCMSS
*enddo
FINISH

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!


!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

MAXSTRESS=-999999999
MINSTRESS=999999999
MAXPSTRAIN=-999999999
MINPSTRAIN=999999999
MAXCSTRAIN=-999999999
MINCSTRAIN=999999999
MAXESTRAIN=-999999999
MINESTRAIN=999999999
MAXTEMP=-999999999
MINTEMP=999999999

STRESSPT1=999999999
*IF, mrat, EQ, 1, THEN
STRESSPT1=-999999999
*ENDIF

MAXPSTRAINCYC1=-999999999
MINPSTRAINCYC1=999999999
MAXPSTRAINCYC2=-999999999
MINPSTRAINCYC2=999999999

MAXSTRESSCYC1=-999999999
MINSTRESSCYC1=999999999
MAXSTRESSCYC2=-999999999
MINSTRESSCYC2=999999999

*DO,curloadstep,1,tot_load_steps

/Post1
/OUTPUT, C:\Simulations\FEA_Junk3,txt
RSYS,0                ! global

ALLSEL
```

```
*get,numelem,ELEM,,COUNT
*DO,t,1,LOADSUBS(1,curloadstep),1

SET,curloadstep,t
ETABLE, TEMPVAL, BFE, TEMP
ETABLE, ESTRAVAL, EPEL, Z
ETABLE, PSTRAVAL, EPPL, Z
ETABLE, CSTRAVAL, EPCR, Z
ETABLE, STRESVAL, S, Z
ETABLE, TSTRAVAL, EPTO, Z
*GET,RES1, ELEM, 1, ETAB,TEMPVAL
*GET,RES2, ELEM, 1, ETAB,ESTRAVAL
*GET,RES3, ELEM, 1, ETAB,PSTRAVAL
*GET,RES4, ELEM, 1, ETAB,CSTRAVAL
*GET,RES5, ELEM, 1, ETAB,STRESVAL
*GET,RES6, ELEM, 1, ETAB, TSTRAVAL
*GET,RESTIME, ACTIVE,0, SET, TIME

*CFOPEN,
C:\Simulations\FEA_%tmt%_%tmca%_%sr%_%mrat%_%ang%_%holdtime%,data,,append
*VWRITE, RESTIME, RES1, RES2, RES3, RES4, RES6, RES5
(E11.5,6X F10.2,6X E11.5,6X E11.5,6X E11.5,6X E11.5,6X F10.4)

*IF,RES5,GT,MAXSTRESS,THEN
MAXSTRESS=RES5
*ENDIF
*IF,RES5,LT,MINSTRESS,THEN
MINSTRESS=RES5
*ENDIF

*IF,RES2,GT,MAXESTRAIN,THEN
MAXESTRAIN=RES2
*ENDIF
*IF,RES2,LT,MINESTRAIN,THEN
MINESTRAIN=RES2
*ENDIF

*IF,RES3,GT,MAXPSTRAIN,THEN
MAXPSTRAIN=RES3
*ENDIF
*IF,RES3,LT,MINPSTRAIN,THEN
MINPSTRAIN=RES3
*ENDIF

*IF,RES4,GT,MAXCSTRAIN,THEN
MAXCSTRAIN=RES4
```

```
*ENDIF
*IF,RES4,LT,MINCSTRAIN,THEN
MINCSTRAIN=RES4
*ENDIF

*IF,RES1,GT,MAXTEMP,THEN
MAXTEMP=RES1
*ENDIF
*IF,RES1,LT,MINTEMP,THEN
MINTEMP=RES1
*ENDIF

*IF, mrat, NE, 1, THEN
*IF,RES5,LT,STRESSPT1,AND,curloadstep,EQ,2,THEN
STRESSPT1=RES5
*ENDIF
*ENDIF

*IF, mrat, EQ, 1, THEN
*IF,RES5,GT,STRESSPT1,AND,curloadstep,EQ,2,THEN
STRESSPT1=RES5
*ENDIF
*ENDIF

*IF, curloadstep,GE,3,AND,curloadstep,LE,6,THEN
*IF,RES5,LT,MINSTRESSCYC1,THEN
MINSTRESSCYC1=RES5
*ENDIF
*ENDIF

*IF, curloadstep,GE,3,AND,curloadstep,LE,6,THEN
*IF,RES5,GT,MAXSTRESSCYC1,THEN
MAXSTRESSCYC1=RES5
*ENDIF
*ENDIF

*IF, curloadstep,GE,7,AND,curloadstep,LE,10,THEN
*IF,RES5,LT,MINSTRESSCYC2,THEN
MINSTRESSCYC2=RES5
*ENDIF
*ENDIF


*IF, curloadstep,GE,7,AND,curloadstep,LE,10,THEN
*IF,RES5,GT,MAXSTRESSCYC2,THEN
MAXSTRESSCYC2=RES5
```

```
*ENDIF
*ENDIF

*IF,t,EQ,LOADSUBS(1,2),AND,curloadstep,EQ,2,THEN
STRESSPT2=RES5
TEMPPT2=RES1
*ENDIF

*IF,t,EQ,LOADSUBS(1,6),AND,curloadstep,EQ,6,THEN
STRESSPT3=RES5
TEMPPT3=RES1
*ENDIF

*IF,t,EQ,LOADSUBS(1,3),AND,curloadstep,EQ,3,THEN
STRESSPT4=RES5
TEMPPDWELLCYC1=RES1
*ENDIF

*IF,t,EQ,LOADSUBS(1,7),AND,curloadstep,EQ,7,THEN
STRESSPT5=RES5
TEMPPT5=RES1
*ENDIF

*IF,t,EQ,LOADSUBS(1,4),AND,curloadstep,EQ,4,THEN
STRESSPT6=RES5
TEMPPT6=RES1
*ENDIF

*IF,t,EQ,LOADSUBS(1,8),AND,curloadstep,EQ,8,THEN
STRESSPT7=RES5
TEMPPT7=RES1
*ENDIF

*IF,t,EQ,LOADSUBS(1,10),AND,curloadstep,EQ,10,THEN
STRESSPT8=RES5
TEMPVDWELLCYC3=RES1
*ENDIF

*IF,t,EQ,LOADSUBS(1,5),AND,curloadstep,EQ,5,THEN
STRESSPT9=RES5
TEMPPT9=RES1
*ENDIF

*IF,t,EQ,LOADSUBS(1,9),AND,curloadstep,EQ,9,THEN
STRESSPT10=RES5
TEMPPT10=RES1
```

```
*ENDIF

*IF,t,EQ,LOADSUBS(1,11),AND,curloadstep,EQ,11,THEN
STRESSPT11=RES5
TEMPPT11=RES1
*ENDIF

*IF,t,EQ,LOADSUBS(1,12),AND,curloadstep,EQ,12,THEN
STRESSPT12=RES5
TEMPPDWELLCYC3=RES1
*ENDIF

*IF,t,EQ,LOADSUBS(1,13),AND,curloadstep,EQ,13,THEN
STRESSPT13=RES5
TEMPPT13=RES1
*ENDIF

*IF,t,EQ,LOADSUBS(1,14),AND,curloadstep,EQ,14,THEN
STRESSPT14=RES5
TEMPPT14=RES1
*ENDIF

*IF, curloadstep,GE,3,AND,curloadstep,LE,6,THEN
*IF,RES3,LT,MINPSTRAINCYC1,THEN
MINPSTRAINCYC1=RES3
*ENDIF
*ENDIF

*IF, curloadstep,GE,3,AND,curloadstep,LE,6,THEN
*IF,RES3,GT,MAXPSTRAINCYC1,THEN
MAXPSTRAINCYC1=RES3
*ENDIF
*ENDIF

*IF, curloadstep,GE,7,AND,curloadstep,LE,10,THEN
*IF,RES3,LT,MINPSTRAINCYC2,THEN
MINPSTRAINCYC2=RES3
*ENDIF
*ENDIF

*IF, curloadstep,GE,7,AND,curloadstep,LE,10,THEN
*IF,RES3,GT,MAXPSTRAINCYC2,THEN
MAXPSTRAINCYC2=RES3
*ENDIF
*ENDIF
```

```
*ENDDO

*ENDDO

PSTRAINRNGCYC1=abs(MAXPSTRAINCYC1-MINPSTRAINCYC1)
PSTRAINRNGCYC2=abs(MAXPSTRAINCYC2-MINPSTRAINCYC2)
SRELAXCYC1=abs(abs(STRESSPT4)-abs(STRESSPT2))
SRELAXCYC2=abs(abs(STRESSPT5)-abs(STRESSPT3))

RELAXPDWELLCYC3=abs(abs(STRESSPT11)-abs(STRESSPT8))
RELAXVDWELLCYC3=abs(abs(STRESSPT13)-abs(STRESSPT12))

*IF, mrat, EQ, -1, THEN
RELAXCOMPCYC3=RELAXPDWELLCYC3
RELAXTENCYC3=RELAXVDWELLCYC3
TEMPCOMPCYC3=TEMPPDWELLCYC3
TEMPTENCYC3=TEMPVDWELLCYC3
SMINCYC3=STRESSPT8
TMINCYC3=TEMPVDWELLCYC3
SMAXCYC3=STRESSPT12
TMAXCYC3=TEMPPDWELLCYC3
*ENDIF

*IF, mrat, GE, 0, THEN
RELAXCOMPCYC3=RELAXVDWELLCYC3
RELAXTENCYC3=RELAXPDWELLCYC3
TEMPCOMPCYC3=TEMPVDWELLCYC3
TEMPTENCYC3=TEMPPDWELLCYC3
SMINCYC3=STRESSPT12
TMINCYC3=TEMPPDWELLCYC3
SMAXCYC3=STRESSPT8
TMAXCYC3=TEMPVDWELLCYC3
*ENDIF

*CFOPEN, C:\Simulations\FEA_P_%st%_%cl%_%ph%,data,,append
*VWRITE, sr, tmt, tmca, re, strain_rate, total_cycles, ang, holdtime, TMINCYC3, SMINCYC3,
TMAXCYC3, SMAXCYC3, TEMPCOMPCYC3, RELAXCOMPCYC3, TEMPTENCYC3,
RELAXTENCYC3
(e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x
f10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x f10.3)

*CFOPEN,
C:\Simulations\FEA_%tmt%_%tmca%_%sr%_%mrat%_%ang%_%holdtime%,data,,append
PARAMETERS='PARAMETERS'
*VWRITE, PARAMETERS
%C
```

```
*VWRITE, sr, tmt, tmca, re, strain_rate, total_cycles, ang, ph, st, cl, ten_hold, comp_hold
(e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3, 6x f10.3, 6x a8, 6x a8, 6x a8, 6x e10.3,
6x e10.3)
EXTREME_VALUES='EXTREME_VALUES'
*VWRITE, EXTREME_VALUES
%C
*VWRITE, MAXTEMP,MINTEMP, MAXESTRAIN, MINESTRAIN, MAXPSTRAIN,
MINPSTRAIN, MAXCSTRAIN, MINCSTRAIN, MAXSTRESS, MINSTRESS
(F10.2,6X F10.2, 6X E11.5, 6X E11.5,6X E11.5, 6X E11.5,6X E11.5, 6X E11.5,6X F10.4,6X
F10.4)

*CFOPEN, C:\Simulations\FEA_CLEANED_%st%_%cl%_%ph%,data,,append
*VWRITE, sr, tmt, tmca, re, strain_rate, total_cycles, ang,holdtime, MAXTEMP,MINTEMP,
MAXESTRAIN, MINESTRAIN, MAXPSTRAIN, MINPSTRAIN, MAXCSTRAIN,
MINCSTRAIN, MAXSTRESS, MINSTRESS
(e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x F10.2,6X F10.2,
6X E11.5, 6X E11.5,6X E11.5, 6X E11.5,6X E11.5, 6X E11.5,6X F10.4,6X F10.4)

*CFOPEN, C:\Simulations\FEA_CLEANED2_%st%_%cl%_%ph%,data,,append

*VWRITE, sr, tmt, tmca, re, strain_rate, total_cycles, ang, holdtime, STRESSPT1,
SRELAXCYC1, SRELAXCYC2, MINSTRESSCYC1, MAXSTRESSCYC1,
MINSTRESSCYC2, MAXSTRESSCYC2, PSTRAINRNGCYC1, PSTRAINRNGCYC2
(e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6X F10.4, 6X F10.4,
6X F10.4, 6X F10.4, 6X F10.4, 6X F10.4, 6X F10.4, 6X E11.5, 6X E11.5)

/OUTPUT,C:\Simulations\FEA_Junk5,txt

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!


!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!
! Create index files for each output file set
*CFOPEN, C:\Simulations\FEA_Index_%st%_%cl%_%ph%,txt,,append
JOB_NAME1='FEA_%tmt%_%tmc%_%sr%_'
JOB_NAME2='%mrat%_%ang%_%holdtime%.data'
*VWRITE, JOB_NAME1,JOB_NAME2
%C%C
/OUTPUT,C:\Simulations\FEA_Junk2,txt
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!


!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
! Parametric Simulation Termination
!
```

```
I=I+1
J=J+1
K=K+1
L=L+1
M=M+1
FINISH
*ENDDO
*ENDDO
*ENDDO
*ENDDO
*ENDDO

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
```

Appendix C: Notched Code

```
!Combined Parametric with Thermocycling of a V notch cylindrical specimen
!Thomas Bouchenot
!Rev 52
!6-23-13
!notes:
!	Notched specimen TMF code. Material properties removed for publication.

Finish
/Clear
/PREP7
/OUTPUT,junk,txt

!*****************************************************************************
**

! Parametric Parameters

! Thermal and loading:
isotherm=1.0		! 0=Yes, 1=No
SINGLEHOLD=1			! 0=two holds (normal), 1= single hold at the max temperature
holdnumber_ini=1	! For use when singlehold=1
holdnumber_inc=2	! 1=0hr, 2=5hr, 3=20hr
holdnumber_fin=1
tmt_ini=100.0 !100	! Initial Min temperature [degrees C]
tmt_inc=850.0		! Increment Min temperature [degrees C]
tmt_fin=950.0		! Final Min temperature [degrees C]
tmc_ini=100.0 !100	! Initial Max temperature [degrees C]
tmc_inc=850.0			! Increment Max temperature [degrees C]
tmc_fin=950.0 !1050.0			! Final Max temperature [degrees C]

! Mechanical Cycling
sr_ini=0.004	!0.001	! Initial Strain range [mm/mm]
sr_inc=0.0005		! Increment Strain range  [mm/mm]
sr_fin=0.004	!0.03		! Final Strain range [mm/mm]
mrat_ini=1			! -1=ZtC, 0=CR, 1=ZtT, 2= SR of 0.05
mrat_inc=-1
mrat_fin=1

! Material Orientation
ang_ini=90.0	! 90 is L-oriented 0 is T-oriented
ang_inc=-90.0 !-45.0
ang_fin=90.0 !90.0

!*****************************************************************************
**
```

```
! Input parameters:

! Geometric:

DIA_NTCH=.25*25.4                                   !notch diameter [mm]
ANG_NTCH=60                                         !notch angle [deg]
RAD_NTCH=.013*25.4                                  !notch radius [mm]
Kts=3.0

DIA_RED=.3*25.4                                     ! Reduced diameter of specimen
        [mm]
RAD_SHLD=1.3*25.4                                   ! Radius of reduction shoulder
        [mm]
DIA_GRIP=.5*25.4                              ! Diameter of specimen grip   [mm]
LEN_GRIP=1*25.4                                     ! Length of specimen grip      [mm]
LEN_BAR=4*25.4                                      ! Total length of specimen     [mm]

!*************************************************************************
**

! Parametric Start and Naming

I=1

*DO,tmc,tmc_ini,tmc_fin,tmc_inc             ! Compressive temperature [degrees C]
*DO,tmt,tmt_ini,tmt_fin,tmt_inc             ! Tensile temperature [degrees C]
*DO,ang,ang_ini,ang_fin,ang_inc             ! Strain range [mm/mm]
*DO,mrat,mrat_ini,mrat_fin,mrat_inc                 ! Strain ratio [unitless]
*DO,holdnumber,holdnumber_ini,holdnumber_fin,holdnumber_inc         !hold time for single
hold
*DO,sr,sr_ini,sr_fin,sr_inc             ! Strain range [mm/mm]

PARSAV,,parameters,txt
*IF,I,GT,1,THEN
finish
/clear
/PREP7
PARRES,,parameters,txt
*ENDIF

finish
/FILNAME, ParametricVNotchedTensileTMF
/title, ParametricVNotchedTensileTMF

/prep7
```

```
/OUTPUT,junk1,txt

!*****************************************************************************
**

! Dwells

*IF, holdnumber, EQ, 1, THEN
holdtime=1.02e-2/3600
*ENDIF

*IF, holdnumber, EQ, 2, THEN
holdtime=5
*ENDIF

*IF, holdnumber, EQ, 3, THEN
holdtime=20
*ENDIF

!*****************************************************************************
**

! Parameters Derived From Geometric Relationships:

*AFUN, DEG
l1=LEN_BAR/2.0
l2=LEN_GRIP
d1=DIA_GRIP/2.0
d2=DIA_RED/2.0
r1=RAD_SHLD
r2=RAD_NTCH
t=DIA_NTCH/2.0
a=ANG_NTCH/2.0
x1=d2+r1-d1
y1=sqrt((r1*r1)-(x1*x1))
x2=sin(a)*r2
y2=cos(a)*r2
x3=(y2/tan(a))-(r2-x2)-t
y3=tan(a)*(d2+x3)

!*****************************************************************************
**

! Specimen Geometry:

CYLIND, d1,,l1,l1-l2
```

```
CYLIND, d1,,l1-l2-y1,l1-l2
WPOFFS, , , l1-l2-y1
TORUS, , r1, d2+r1
WPOFFS, , , -(l1-l2-y1)
VSBV, 2, 3
CYLIND, d2,,l1-l2-y1,y3
CONE, t+r2-x2, d2, y3, y2
CYLIND, t+r2-x2,,y2,0
TORUS, , r2, t+r2
VSBV, 5, 6

CYLIND, t,,-y2,0
VADD,5,7
CYLIND, t,,-y2,0
VSBV, 6,5

ALLSEL

VADD,ALL

BLC5,0,-d1,2*d1,2*d1,l1
VSBV, 5,1

VSYMM,Z,ALL,,,,0,0

VADD,ALL

HPTCREATE, line, 1,99, coord, 0, 0, -l1                    ! Create a Hard Point to make sure a
node

is placed on the origin of the graph for the BCs
HPTCREATE, line, 39, 98, coord, 0, 0, l1
allsel

!*****************************************************************************
**

! Define a local system to transform material properties into desired orientation

local,11,0,0,0,0,0,0,ang,,        ! use this one to rotate in the transverse plane..
ESYS,11                    ! the local system is selected for all defined elements

!*****************************************************************************
**

! Material properties removed for publication
```

```
!***************************************************************************
**

! Meshing Element Type:

ET,1,SOLID187                               ! Element is a solid 185 8-node structural
solid

element
MSHAPE, 1, 3D                               ! Mesh with tetrahedral-shaped elements
MSHKEY, 0                             ! Free mesh

!***************************************************************************
**

! Meshing:

MOPT, TETEXPND, 2
ESIZE, 2.5

lesize,5,,,5                  !top of grip
lesize,6,,,5
lesize,39,,,5
lesize,1,,,5
lesize,29,,,5
lesize,30,,,5

lesize,9,,,12,                !length of grip
lesize,10,,,12,
lesize,2,,,12,
lesize,22,,,12,

lesize,3,,,5                  !bottom of grip/top of reduced
lesize,4,,,5
lesize,25,,,5
lesize,26,,,5

lesize,35,,,10,(d2/d1)        !length of reduced
lesize,36,,,10, (d2/d1)
lesize,7,,,10, (d2/d1)
lesize,21,,,10, (d2/d1)

lesize,19,,,5                 !bottom of reduced/top of gage
lesize,20,,,5
lesize,32,,,5
```

```
lesize,31,,,5

lesize,23,,,22,30/5          !length of gage
lesize,24,,,22,30/5
lesize,18,,,22,30/5
lesize,8,,,22,30/5

lesize,13,,,30               !bottom of gage/top of angled
lesize,14,,,30
lesize,34,,,30
lesize,33,,,30

lesize,41,,,3,((t+r2-x2)/d2)  !length of angle
lesize,42,,,3,((t+r2-x2)/d2)
lesize,11,,,3,((t+r2-x2)/d2)
lesize,17,,,3,((t+r2-x2)/d2)

lesize,27,,,30               !bottom of angle/top of notch
lesize,28,,,30
lesize,38,,,30
lesize,37,,,30

lesize,45,,,2,(t/(t+r2-x2))   !length of notch
lesize,46,,,2,(t/(t+r2-x2))
lesize,16,,,2,(t/(t+r2-x2))
lesize,12,,,2,(t/(t+r2-x2))

lesize,15,,,30               !bottom of notch
lesize,43,,,30
lesize,44,,,30

VMESH,all

lsel,s,,,43,44
nsll,s,1
esln,s
erefine,all,,,2,1            !refine notch tip

allsel

!*****************************************************************************
**

! Mechanical Loading:
```

```
strain_range = sr                                  ! Difference in Max and Min strains

[mm/mm]
strain_rate = 0.001                                ! Strain rate [mm/mm/s]
tol=0.0001
re=(mrat-1+tol)/(mrat+1+tol)                       ! Strain ratio (0=ZtT,-1=CR,-900=ZtC)
strain_ratio=re                                    ! Frequency of data capture
tens_hold = 18.0 !1.00e-2/3600                          ! Tension hold [hr]
comp_hold = 1.02e-2/3600                           ! Compression hold [hr]
first_hold = 1.01e-2/3600                          !First hold [hr] ex:5000 hr hold
num_cycles = 2                                          ! Number of cycles

! Cyclic Parameters Derived From Relationships:

displ_range = strain_range*LEN_BAR*0.5
displ_max = displ_range/(1.0-strain_ratio)         ! Displacement [mm]
displ_min = displ_max-displ_range                  ! Displacement [mm]
displ_mean = 0.5*(displ_max+displ_min)                  ! Displacement [mm]
strain_rate_hr = strain_rate*3600.0                ! Strain rate [mm/mm/hr]
half_cycle = strain_range/strain_rate_hr/2.0       ! Half cycle [hr]
full_cycle = 2.0*half_cycle                        ! Full cycle [hr]

! Cycle Stepping and Ramping Time

tot_load_steps=num_cycles*4+2

*IF,tmt,NE,tmca,THEN
load_init_time = 2.0E-3/3600.0                          ! Initial Load Time [hr]
*ENDIF

*IF,tmt,EQ,tmca,THEN
load_init_time = 2.0E-2/3600.0                          ! Initial Load Time [hr]
*ENDIF

load_mini_time = 1.0E-4/3600.0                          ! Minimum Deltim step time [hr]
load_mini_dwell_time = 1.0E-4/3600.0                    ! Minimum Deltim step time [hr]
load_maxi_time = 10.0/3600.0                            ! Maximum Deltim step time [hr]
load_maxi_dwell_time = 300                         ! Maximum Deltim step time [hr]
load_ramp_time = 1.0E-10/3600.0                         ! Ramp time used in Deltim [hr]
data_freq = 1.0                                         ! Frequency of data capture

! Temperature Cycling

tmca=tmc
max_temp=0.5*(tmt+tmca+abs(tmt-tmca))
min_temp=0.5*(tmt+tmca-abs(tmt-tmca))
```

```
temp_range=abs(tmt-tmca)

*IF, tmt, NE, tmca, THEN
temp_rate = 3                                    !3 degress per second for TMF
temp_rate_hr = temp_rate*3600.0
half_cycle = temp_range/temp_rate_hr/2.0
full_cycle = 2.0*half_cycle
*ENDIF

!***************************************************************************
**

! Assign the Peak-Valley-Period Values: (modified with Dr. Gordon's rules for clarity)

! Cycling rules:
!       Rule #2: If CR and compression hold exceeds tensile hold, then go to compression first
!     Rule #3: If zero-to-compression, proceed to minimum displacement first
!     Rule #4: If zero-to-tension, proceed to maximum displacement first
!     Rule #5: Initial portion of the cycle goes from zero-displacement and mean temp

peak_displ=displ_max
valley_displ=displ_min
peak_hold=tens_hold
valley_hold=comp_hold
mean_temp=0.5*(tmt+tmca)
temp_init=mean_temp
peak_temp=tmt
valley_temp=tmca

*IF, SINGLEHOLD, EQ, 0, THEN
*IF,mrat,eq,0,and,comp_hold,gt,tens_hold,THEN ! See Rule #2
peak_displ=displ_min
valley_displ=displ_max
*ENDIF
*ENDIF

*IF,mrat,eq,-1,THEN ! See Rule #3 (only in Z-to-C case)
peak_displ=displ_min
valley_displ=displ_max
peak_hold=comp_hold
valley_hold=tens_hold
half_cycle=half_cycle*2
peak_temp=tmca
valley_temp=tmt
temp_init=tmt
*ENDIF
```

```
*IF,mrat,eq,1,THEN   ! See Rule #4 (only in Z-to-T case)
peak_displ=displ_max
valley_displ=displ_min
peak_hold=tens_hold
valley_hold=comp_hold
half_cycle=half_cycle*2
peak_temp=tmt
valley_temp=tmca
temp_init=tmca
*ENDIF

*IF,mrat,eq,-1,THEN ! See Rule #5
init_period_hr=half_cycle*peak_displ/displ_range   ! Period of Step 1 cycle [hr]
displ_init=0                                       ! Initial displacement for Step 0 [mm]
*ENDIF

!***************************************************************************
**

! For hold only at max temp
*IF, SINGLEHOLD, EQ, 1, THEN
*IF, peak_temp, GE, valley_temp, THEN
peak_hold=holdtime
valley_hold=1.01e-2/3600
*ENDIF

*IF, peak_temp, LT, valley_temp, THEN
peak_hold=1.01e-2/3600
valley_hold=holdtime
*ENDIF

!*IF, peak_temp, EQ, valley_temp, THEN
!peak_hold=holdtime
!valley_hold=holdtime
!*ENDIF

*ENDIF

!***************************************************************************
**

! Fixing the substep times !changed /20 to /40

load_init_dwell_time_peak = 1.0E-2/3600.0
load_init_dwell_time_valley = 1.0E-2/3600.0
```

```
load_init_dwell_time_first = 1.0E-2/3600.0

*IF, first_hold, GT, 2.0E-2/3600, THEN
load_init_dwell_time_first = first_hold/40
*ENDIF

*IF, peak_hold, GT, 2.0E-2/3600, THEN
load_init_dwell_time_peak = peak_hold/40
*ENDIF

*IF, valley_hold, GT, 2.0E-2/3600, THEN
load_init_dwell_time_valley = valley_hold/40
*ENDIF

!*****************************************************************************
**

! Boundary Conditions:

!ESYS, 0
KSEL, S, ,,99
NSLK, S
D,ALL,UY,0
D,ALL,UX,0
ALLSEL

KSEL, S, ,,98
NSLK, S
D,ALL,UY,0
D,ALL,UX,0
ALLSEL

ASEL, S, ,,4
NSLA, S, 1
D,ALL,UZ,0
ALLSEL

ASEL,S,,,1
ASEL,A,,,15
DA, ALL, UY, 0
ALLSEL

!*****************************************************************************
**

! Create Node Groups:
```

```
! Top Nodes - TOP
ASEL, S, ,,12
NSLA, S, 1
CM, TOP , NODE
ALLSEL

FINISH

ALLSEL

!***************************************************************************
**

! Begin Initial Solution Stage
/CONFIG,NRES,500000
/NERR,5000000,5000000,,0
/SOLU
ALLSEL

! Step 1
total_time = abs(load_ramp_time)                    ! Total time [s]
Antype, trans
nropt,auto                                          ! Uses Newton-Raphson
lnsrch,auto                                         ! Auto line searching for NR
NLGEOM,auto                                         ! Non-linear geometry
Solcontrol, 1                                       ! Optimizes nonlinear solutions
Cnvtol,F,3
Time, total_time                                    ! Time at end of step
!NSUBST,20,1000,20                                  ! Specifies substeps
Deltim, load_init_time, load_mini_time, load_maxi_time
Autots, 1                                           ! Auto Time Stepping
D, TOP , UZ , displ_init
BF,ALL,TEMP,temp_init                                       ! Nodal body force load
Outres, All, data_freq                              ! Outputs data to be read by ESOL
Crplim, 20, 1                                       ! Creep Ratio Limit
Rate, 1                                             ! Activates Creep for step
Kbc, 0
Solve

! Step 2:
total_time = abs(half_cycle)+total_time
Antype, trans
nropt,auto
lnsrch,auto
NLGEOM,auto
```

```
Solcontrol, 1
Cnvtol,F,3
Time, total_time
!NSUBST,20,1000,20
Deltim, load_init_time, load_mini_time, load_maxi_time

Autots, 1
D, TOP , UZ , peak_displ
!NSEL,ALL
BF,ALL,TEMP,peak_temp
Outres, All, data_freq
Crplim, 20, 1
Rate, 1
Kbc, 0
Solve

!*****************************************************************************
**

! Continue Solution Stage with Subsequent Cycling
total_cycles=num_cycles
*do,cycle,1,total_cycles,1

! Step 3:
*GET, LOADNUM,ACTIVE,0,SOLU, NCMLS
!*IF, LOADNUM, EQ, 2, THEN
!total_time = abs(first_hold) + total_time
!*ELSE
total_time = abs(peak_hold) + total_time
!*ENDIF
Antype, trans
nropt,auto
lnsrch,auto
NLGEOM,auto
Solcontrol, 1
Cnvtol,F,3
Time, total_time
!NSUBST,20,1000,20
!*IF, LOADNUM, EQ, 2, THEN
!Deltim, load_init_dwell_time_first, load_mini_dwell_time, load_maxi_dwell_time
!*ELSE
Deltim, load_init_dwell_time_peak, load_mini_dwell_time, load_maxi_dwell_time
!*ENDIF
Autots, 1
D, TOP , UZ , peak_displ
NSEL,ALL
```

```
BF,ALL,TEMP,peak_temp
Outres, All, data_freq
Crplim, 20, 1
Rate, 1
Kbc, 0
Solve

! Step 4:
total_time = abs(full_cycle) + total_time
Antype, trans
nropt,auto
lnsrch,auto
NLGEOM,auto
Solcontrol, 1
Cnvtol,F,3
Time, total_time
!NSUBST,20,1000,20
Deltim, load_init_time, load_mini_time, load_maxi_time
Autots, 1
D, TOP , UZ , valley_displ
NSEL,ALL
BF,ALL,TEMP,valley_temp
Outres, All, data_freq
Crplim, 20, 1
Rate, 1
Kbc, 0
Solve

! Step 5:
total_time = abs(valley_hold) + total_time
Antype, trans
nropt,auto
lnsrch,auto
NLGEOM,auto
Solcontrol, 1
Cnvtol,F,3
Time, total_time
!NSUBST,20,1000,20
Deltim, load_init_dwell_time_valley, load_mini_dwell_time, load_maxi_dwell_time
Autots, 1
D, TOP , UZ , valley_displ
NSEL,ALL
BF,ALL,TEMP,valley_temp
Outres, all, data_freq
Crplim, 20, 1
Rate, 1
```

```
Kbc, 0
Solve

! Step 6:
total_time = abs(full_cycle) + total_time
Antype, trans
nropt,auto
lnsrch,auto
NLGEOM,auto
Solcontrol, 1
Cnvtol,F,3
Time, total_time
!NSUBST,25,1000,20
Deltim, load_init_time, load_mini_time, load_maxi_time
Autots, 1
D, TOP , UZ , peak_displ
NSEL,ALL
BF,ALL,TEMP,peak_temp
Outres, all, data_freq
Crplim, 20, 1
Rate, 1
Kbc, 0
Solve
*enddo
FINISH

!*******************************************************************************
**

!Post-processing

/Post1
!SAVE,ParametricVNotchedTensileTMF,DB,,all
/OUTPUT, FEA_Junk3,txt
ALLSEL
RSYS,0
csys, 0

maxstressc1n=-999999999
minstressc1n=999999999
maxstressc2n=-999999999
minstressc2n=999999999
maxstressc3n=-999999999
minstressc3n=999999999

*GET,LSTSET, ACTIVE, 0, SET, NSET
```

```
*DO,t,1,LSTSET,1
SET,,,,,,,t

*GET,curlo, ACTIVE, 0, SET, LSTP
*GET,cursb, ACTIVE, 0, SET, SBST
*GET,lsubs, ACTIVE, 0, SET, NSET, LAST, curlo
*GET,RESTIME, ACTIVE,0, SET, TIME

! Whole Specimen

ALLSEL

ksel, s, , , 33
nslk, s
esln, s

ETABLE, ESTRVALN, EPEL, Z
ETABLE, PSTRVALN, EPPL, Z
ETABLE, CSTRVALN, EPCR, Z
ETABLE, TSTRVALN, EPTO, Z
ETABLE, STRSVALN, S, Z
ETABLE, TEMPVAL, BFE, TEMP

ESORT,ETAB,STRSVALN, , 1
*get,ntchelem,sort,,imax

*get, MAXSTRESSN,ELEM,ntchelem,ETAB,STRSVALN
*get, MAXESTRN,ELEM,ntchelem,ETAB,ESTRVALN
*get, MAXPSTRN,ELEM,ntchelem,ETAB,PSTRVALN
*get, MAXCSTRN,ELEM,ntchelem,ETAB,CSTRVALN
*get, MAXTSTRN,ELEM,ntchelem,ETAB,TSTRVALN

ESORT,ETAB,TEMPVAL, , 1
*get,MAXTEMP,sort,,max

*CFOPEN, FEA_N_%tmt%_%tmc%_%sr%_%mrat%_%ang%_%holdtime%,data,,append
*VWRITE, RESTIME,curlo, cursb, MAXTEMP, MAXESTRN, MAXPSTRN, MAXCSTRN,
MAXTSTRN, MAXSTRESSN
(E11.5,6X F10.2,6X F10.2,6X F10.2,6X E11.5,6X E11.5,6X E11.5,6X E11.5,6X F10.3)

! Only Grip

allsel

NSEL, S, LOC, Z, l1-5, l1-10, , 1
ESLN, S, 0
```

```
ETABLE, ESTRVALG, EPEL, Z
ETABLE, PSTRVALG, EPPL, Z
ETABLE, CSTRVALG, EPCR, Z
ETABLE, TSTRVALG, EPTO, Z
ETABLE, STRSVALG, S, Z

ESORT,ETAB,STRSVALG, , 1
*get,gripelem,sort,,imax

*get, MAXSTRESSG,ELEM,gripelem,ETAB,STRSVALG
*get, MAXESTRG,ELEM,gripelem,ETAB,ESTRVALG
*get, MAXPSTRG,ELEM,gripelem,ETAB,PSTRVALG
*get, MAXCSTRG,ELEM,gripelem,ETAB,CSTRVALG
*get, MAXTSTRG,ELEM,gripelem,ETAB,TSTRVALG

*CFOPEN, FEA_G_%tmt%_%tmc%_%sr%_%mrat%_%ang%_%holdtime%,data,,append
*VWRITE, RESTIME,curlo, cursb, MAXTEMP, MAXESTRG, MAXPSTRG, MAXCSTRG,
MAXTSTRG, MAXSTRESSG
(E11.5,6X F10.2,6X F10.2,6X F10.2,6X E11.5,6X E11.5,6X E11.5,6X E11.5,6X F10.3)

! Summary Results File Data

*IF, mrat, GE, 0, THEN

*IF, curlo, EQ, 2 , and, MAXSTRESSN, GE, maxstressc1n, THEN
maxstressc1n=MAXSTRESSN
maxstressc1g=MAXSTRESSG
maxestrainc1n=MAXESTRN
maxestrainc1g=MAXESTRG
maxpstrainc1n=MAXPSTRN
maxpstrainc1g=MAXPSTRG
maxcstrainc1n=MAXCSTRN
maxcstrainc1g=MAXCSTRG
maxtstrainc1n=MAXTSTRN
maxtstrainc1g=MAXTSTRG
maxtempc1n=MAXTEMP
maxtempc1g=MAXTEMP
*ENDIF

*IF, curlo, EQ, 3 , and, t, EQ, lsubs, THEN
maxholdstressc1n=MAXSTRESSN
maxholdstressc1g=MAXSTRESSG
maxholdestrainc1n=MAXESTRN
maxholdestrainc1g=MAXESTRG
maxholdpstrainc1n=MAXPSTRN
```

```
maxholdpstrainc1g=MAXPSTRG
maxholdcstrainc1n=MAXCSTRN
maxholdcstrainc1g=MAXCSTRG
maxholdtstrainc1n=MAXTSTRN
maxholdtstrainc1g=MAXTSTRG
maxholdtempc1n=MAXTEMP
maxholdtempc1g=MAXTEMP
*ENDIF

*IF, curlo, EQ, 4 , and, MAXSTRESSN, LE, minstressc1n, THEN
minstressc1n=MAXSTRESSN
minstressc1g=MAXSTRESSG
minestrainc1n=MAXESTRN
minestrainc1g=MAXESTRG
minpstrainc1n=MAXPSTRN
minpstrainc1g=MAXPSTRG
mincstrainc1n=MAXCSTRN
mincstrainc1g=MAXCSTRG
mintstrainc1n=MAXTSTRN
mintstrainc1g=MAXTSTRG
mintempc1n=MAXTEMP
mintempc1g=MAXTEMP
*ENDIF

*IF, curlo, EQ, 5 , and, t, EQ, lsubs, THEN
minholdstressc1n=MAXSTRESSN
minholdstressc1g=MAXSTRESSG
minholdestrainc1n=MAXESTRN
minholdestrainc1g=MAXESTRG
minholdpstrainc1n=MAXPSTRN
minholdpstrainc1g=MAXPSTRG
minholdcstrainc1n=MAXCSTRN
minholdcstrainc1g=MAXCSTRG
minholdtstrainc1n=MAXTSTRN
minholdtstrainc1g=MAXTSTRG
minholdtempc1n=MAXTEMP
minholdtempc1g=MAXTEMP
*ENDIF

*IF, curlo, EQ, 6 , and, MAXSTRESSN, GE, maxstressc2n, THEN
maxstressc2n=MAXSTRESSN
maxstressc2g=MAXSTRESSG
maxestrainc2n=MAXESTRN
maxestrainc2g=MAXESTRG
maxpstrainc2n=MAXPSTRN
maxpstrainc2g=MAXPSTRG
```

```
maxcstrainc2n=MAXCSTRN
maxcstrainc2g=MAXCSTRG
maxtstrainc2n=MAXTSTRN
maxtstrainc2g=MAXTSTRG
maxtempc2n=MAXTEMP
maxtempc2g=MAXTEMP
*ENDIF

*IF, curlo, EQ, 7 , and, t, EQ, lsubs, THEN
maxholdstressc2n=MAXSTRESSN
maxholdstressc2g=MAXSTRESSG
maxholdestrainc2n=MAXESTRN
maxholdestrainc2g=MAXESTRG
maxholdpstrainc2n=MAXPSTRN
maxholdpstrainc2g=MAXPSTRG
maxholdcstrainc2n=MAXCSTRN
maxholdcstrainc2g=MAXCSTRG
maxholdtstrainc2n=MAXTSTRN
maxholdtstrainc2g=MAXTSTRG
maxholdtempc2n=MAXTEMP
maxholdtempc2g=MAXTEMP
*ENDIF

*IF, curlo, EQ, 8 , and, MAXSTRESSN, LE, minstressc2n, THEN
minstressc2n=MAXSTRESSN
minstressc2g=MAXSTRESSG
minestrainc2n=MAXESTRN
minestrainc2g=MAXESTRG
minpstrainc2n=MAXPSTRN
minpstrainc2g=MAXPSTRG
mincstrainc2n=MAXCSTRN
mincstrainc2g=MAXCSTRG
mintstrainc2n=MAXTSTRN
mintstrainc2g=MAXTSTRG
mintempc2n=MAXTEMP
mintempc2g=MAXTEMP
*ENDIF

*IF, curlo, EQ, 9 , and, t, EQ, lsubs, THEN
minholdstressc2n=MAXSTRESSN
minholdstressc2g=MAXSTRESSG
minholdestrainc2n=MAXESTRN
minholdestrainc2g=MAXESTRG
minholdpstrainc2n=MAXPSTRN
minholdpstrainc2g=MAXPSTRG
minholdcstrainc2n=MAXCSTRN
```

```
minholdcstrainc2g=MAXCSTRG
minholdtstrainc2n=MAXTSTRN
minholdtstrainc2g=MAXTSTRG
minholdtempc2n=MAXTEMP
minholdtempc2g=MAXTEMP
*ENDIF

*IF, curlo, EQ, 10 , and, MAXSTRESSN, GE, maxstressc3n, THEN
maxstressc3n=MAXSTRESSN
maxstressc3g=MAXSTRESSG
maxestrainc3n=MAXESTRN
maxestrainc3g=MAXESTRG
maxpstrainc3n=MAXPSTRN
maxpstrainc3g=MAXPSTRG
maxcstrainc3n=MAXCSTRN
maxcstrainc3g=MAXCSTRG
maxtstrainc3n=MAXTSTRN
maxtstrainc3g=MAXTSTRG
maxtempc3n=MAXTEMP
maxtempc3g=MAXTEMP
*ENDIF

*IF, curlo, EQ, 11 , and, t, EQ, lsubs, THEN
maxholdstressc3n=MAXSTRESSN
maxholdstressc3g=MAXSTRESSG
maxholdestrainc3n=MAXESTRN
maxholdestrainc3g=MAXESTRG
maxholdpstrainc3n=MAXPSTRN
maxholdpstrainc3g=MAXPSTRG
maxholdcstrainc3n=MAXCSTRN
maxholdcstrainc3g=MAXCSTRG
maxholdtstrainc3n=MAXTSTRN
maxholdtstrainc3g=MAXTSTRG
maxholdtempc3n=MAXTEMP
maxholdtempc3g=MAXTEMP
*ENDIF

*IF, curlo, EQ, 12 , and, MAXSTRESSN, LE, minstressc3n, THEN
minstressc3n=MAXSTRESSN
minstressc3g=MAXSTRESSG
minestrainc3n=MAXESTRN
minestrainc3g=MAXESTRG
minpstrainc3n=MAXPSTRN
minpstrainc3g=MAXPSTRG
mincstrainc3n=MAXCSTRN
mincstrainc3g=MAXCSTRG
```

```
mintstrainc3n=MAXTSTRN
mintstrainc3g=MAXTSTRG
mintempc3n=MAXTEMP
mintempc3g=MAXTEMP
*ENDIF

*IF, curlo, EQ, 13 , and, t, EQ, lsubs, THEN
minholdstressc3n=MAXSTRESSN
minholdstressc3g=MAXSTRESSG
minholdestrainc3n=MAXESTRN
minholdestrainc3g=MAXESTRG
minholdpstrainc3n=MAXPSTRN
minholdpstrainc3g=MAXPSTRG
minholdcstrainc3n=MAXCSTRN
minholdcstrainc3g=MAXCSTRG
minholdtstrainc3n=MAXTSTRN
minholdtstrainc3g=MAXTSTRG
minholdtempc3n=MAXTEMP
minholdtempc3g=MAXTEMP
*ENDIF

*ENDIF

*IF, mrat, EQ, -1, THEN

*IF, curlo, EQ, 2 , and, MAXSTRESSN, LE, minstressc1n, THEN
minstressc1n=MAXSTRESSN
minstressc1g=MAXSTRESSG
minestrainc1n=MAXESTRN
minestrainc1g=MAXESTRG
minpstrainc1n=MAXPSTRN
minpstrainc1g=MAXPSTRG
mincstrainc1n=MAXCSTRN
mincstrainc1g=MAXCSTRG
mintstrainc1n=MAXTSTRN
mintstrainc1g=MAXTSTRG
mintempc1n=MAXTEMP
mintempc1g=MAXTEMP
*ENDIF

*IF, curlo, EQ, 3 , and, t, EQ, lsubs, THEN
minholdstressc1n=MAXSTRESSN
minholdstressc1g=MAXSTRESSG
minholdestrainc1n=MAXESTRN
minholdestrainc1g=MAXESTRG
minholdpstrainc1n=MAXPSTRN
```

```
minholdpstrainc1g=MAXPSTRG
minholdcstrainc1n=MAXCSTRN
minholdcstrainc1g=MAXCSTRG
minholdtstrainc1n=MAXTSTRN
minholdtstrainc1g=MAXTSTRG
minholdtempc1n=MAXTEMP
minholdtempc1g=MAXTEMP
*ENDIF

*IF, curlo, EQ, 4 , and, MAXSTRESSN, GE, maxstressc1n, THEN
maxstressc1n=MAXSTRESSN
maxstressc1g=MAXSTRESSG
maxestrainc1n=MAXESTRN
maxestrainc1g=MAXESTRG
maxpstrainc1n=MAXPSTRN
maxpstrainc1g=MAXPSTRG
maxcstrainc1n=MAXCSTRN
maxcstrainc1g=MAXCSTRG
maxtstrainc1n=MAXTSTRN
maxtstrainc1g=MAXTSTRG
maxtempc1n=MAXTEMP
maxtempc1g=MAXTEMP
*ENDIF

*IF, curlo, EQ, 5 , and, t, EQ, lsubs, THEN
maxholdstressc1n=MAXSTRESSN
maxholdstressc1g=MAXSTRESSG
maxholdestrainc1n=MAXESTRN
maxholdestrainc1g=MAXESTRG
maxholdpstrainc1n=MAXPSTRN
maxholdpstrainc1g=MAXPSTRG
maxholdcstrainc1n=MAXCSTRN
maxholdcstrainc1g=MAXCSTRG
maxholdtstrainc1n=MAXTSTRN
maxholdtstrainc1g=MAXTSTRG
maxholdtempc1n=MAXTEMP
maxholdtempc1g=MAXTEMP
*ENDIF

*IF, curlo, EQ, 6 , and, MAXSTRESSN, LE, minstressc2n, THEN
minstressc2n=MAXSTRESSN
minstressc2g=MAXSTRESSG
minestrainc2n=MAXESTRN
minestrainc2g=MAXESTRG
minpstrainc2n=MAXPSTRN
minpstrainc2g=MAXPSTRG
```

```
mincstrainc2n=MAXCSTRN
mincstrainc2g=MAXCSTRG
mintstrainc2n=MAXTSTRN
mintstrainc2g=MAXTSTRG
mintempc2n=MAXTEMP
mintempc2g=MAXTEMP
*ENDIF

*IF, curlo, EQ, 7 , and, t, EQ, lsubs, THEN
minholdstressc2n=MAXSTRESSN
minholdstressc2g=MAXSTRESSG
minholdestrainc2n=MAXESTRN
minholdestrainc2g=MAXESTRG
minholdpstrainc2n=MAXPSTRN
minholdpstrainc2g=MAXPSTRG
minholdcstrainc2n=MAXCSTRN
minholdcstrainc2g=MAXCSTRG
minholdtstrainc2n=MAXTSTRN
minholdtstrainc2g=MAXTSTRG
minholdtempc2n=MAXTEMP
minholdtempc2g=MAXTEMP
*ENDIF

*IF, curlo, EQ, 8 , and, MAXSTRESSN, GE, maxstressc2n, THEN
maxstressc2n=MAXSTRESSN
maxstressc2g=MAXSTRESSG
maxestrainc2n=MAXESTRN
maxestrainc2g=MAXESTRG
maxpstrainc2n=MAXPSTRN
maxpstrainc2g=MAXPSTRG
maxcstrainc2n=MAXCSTRN
maxcstrainc2g=MAXCSTRG
maxtstrainc2n=MAXTSTRN
maxtstrainc2g=MAXTSTRG
maxtempc2n=MAXTEMP
maxtempc2g=MAXTEMP
*ENDIF

*IF, curlo, EQ, 9 , and, t, EQ, lsubs, THEN
maxholdstressc2n=MAXSTRESSN
maxholdstressc2g=MAXSTRESSG
maxholdestrainc2n=MAXESTRN
maxholdestrainc2g=MAXESTRG
maxholdpstrainc2n=MAXPSTRN
maxholdpstrainc2g=MAXPSTRG
maxholdcstrainc2n=MAXCSTRN
```

```
maxholdcstrainc2g=MAXCSTRG
maxholdtstrainc2n=MAXTSTRN
maxholdtstrainc2g=MAXTSTRG
maxholdtempc2n=MAXTEMP
maxholdtempc2g=MAXTEMP
*ENDIF

*IF, curlo, EQ, 10 , and, MAXSTRESSN, LE, minstressc3n, THEN
minstressc3n=MAXSTRESSN
minstressc3g=MAXSTRESSG
minestrainc3n=MAXESTRN
minestrainc3g=MAXESTRG
minpstrainc3n=MAXPSTRN
minpstrainc3g=MAXPSTRG
mincstrainc3n=MAXCSTRN
mincstrainc3g=MAXCSTRG
mintstrainc3n=MAXTSTRN
mintstrainc3g=MAXTSTRG
mintempc3n=MAXTEMP
mintempc3g=MAXTEMP
*ENDIF

*IF, curlo, EQ, 11 , and, t, EQ, lsubs, THEN
minholdstressc3n=MAXSTRESSN
minholdstressc3g=MAXSTRESSG
minholdestrainc3n=MAXESTRN
minholdestrainc3g=MAXESTRG
minholdpstrainc3n=MAXPSTRN
minholdpstrainc3g=MAXPSTRG
minholdcstrainc3n=MAXCSTRN
minholdcstrainc3g=MAXCSTRG
minholdtstrainc3n=MAXTSTRN
minholdtstrainc3g=MAXTSTRG
minholdtempc3n=MAXTEMP
minholdtempc3g=MAXTEMP
*ENDIF

*IF, curlo, EQ, 12 , and, MAXSTRESSN, GE, maxstressc3n, THEN
maxstressc3n=MAXSTRESSN
maxstressc3g=MAXSTRESSG
maxestrainc3n=MAXESTRN
maxestrainc3g=MAXESTRG
maxpstrainc3n=MAXPSTRN
maxpstrainc3g=MAXPSTRG
maxcstrainc3n=MAXCSTRN
maxcstrainc3g=MAXCSTRG
```

```
maxtstrainc3n=MAXTSTRN
maxtstrainc3g=MAXTSTRG
maxtempc3n=MAXTEMP
maxtempc3g=MAXTEMP
*ENDIF

*IF, curlo, EQ, 13 , and, t, EQ, lsubs, THEN
maxholdstressc3n=MAXSTRESSN
maxholdstressc3g=MAXSTRESSG
maxholdestrainc3n=MAXESTRN
maxholdestrainc3g=MAXESTRG
maxholdpstrainc3n=MAXPSTRN
maxholdpstrainc3g=MAXPSTRG
maxholdcstrainc3n=MAXCSTRN
maxholdcstrainc3g=MAXCSTRG
maxholdtstrainc3n=MAXTSTRN
maxholdtstrainc3g=MAXTSTRG
maxholdtempc3n=MAXTEMP
maxholdtempc3g=MAXTEMP
*ENDIF

*ENDIF

*ENDDO

! Writing Parameters to Individual Files

*CFOPEN, FEA_N_%tmt%_%tmc%_%sr%_%mrat%_%ang%_%holdtime%,data,,append
PARAMETERS='PARAMETERS'
*VWRITE, PARAMETERS
%C
*VWRITE, sr, tmt, tmca, re, strain_rate, total_cycles, ang, ten_hold, comp_hold
(e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x e10.3)

*CFOPEN, FEA_G_%tmt%_%tmc%_%sr%_%mrat%_%ang%_%holdtime%,data,,append
PARAMETERS='PARAMETERS'
*VWRITE, PARAMETERS
%C
*VWRITE, sr, tmt, tmca, re, strain_rate, total_cycles, ang, ten_hold, comp_hold
(e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x e10.3)

! Index File

*CFOPEN, FEA_Index_N,txt,,append
JOB_NAME1='FEA_N_%tmt%_%tmc%_%sr%_'
JOB_NAME2='%mrat%_%ang%_%holdtime%.data'
```

```
*VWRITE, JOB_NAME1,JOB_NAME2
%C%C

*CFOPEN, FEA_Index_G,txt,,append
JOB_NAME1='FEA_G_%tmt%_%tmc%_%sr%_'
JOB_NAME2='%mrat%_%ang%_%holdtime%.data'
*VWRITE, JOB_NAME1,JOB_NAME2
%C%C

! Writing the summary file

*CFOPEN, FEA_CLEANED_N_STRESS_C1,data,,append
*VWRITE, sr, tmt, tmca, re, strain_rate, total_cycles, ang, holdtime,

maxstressc1n,maxtempc1n,maxholdstressc1n,maxholdtempc1n, minstressc1n,mintempc1n,

minholdstressc1n,minholdtempc1n
(e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x f10.3,

6x f10.3, 6x f10.3,6x f10.3, 6x f10.3, 6x f10.3, 6x f10.3 )

*CFOPEN, FEA_CLEANED_G_STRESS_C1,data,,append
*VWRITE, sr, tmt, tmca, re, strain_rate, total_cycles, ang, holdtime,

maxstressc1g,maxtempc1g,maxholdstressc1g,maxholdtempc1g, minstressc1g,mintempc1g,

minholdstressc1g,minholdtempc1g
(e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x f10.3,

6x f10.3, 6x f10.3,6x f10.3, 6x f10.3, 6x f10.3, 6x f10.3 )

*CFOPEN, FEA_CLEANED_N_ESTRAIN_C1,data,,append
*VWRITE, sr, tmt, tmca, re, strain_rate, total_cycles, ang, holdtime,

maxestrainc1n,maxtempc1n,maxholdestrainc1n,maxholdtempc1n, minestrainc1n,mintempc1n,

minholdestrainc1n,minholdtempc1n
(e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3,

6x e10.3, 6x f10.3,6x e10.3, 6x f10.3, 6x e10.3, 6x f10.3 )

*CFOPEN, FEA_CLEANED_G_ESTRAIN_C1,data,,append
*VWRITE, sr, tmt, tmca, re, strain_rate, total_cycles, ang, holdtime,

maxestrainc1g,maxtempc1g,maxholdestrainc1g,maxholdtempc1g, minestrainc1g,mintempc1g,
```

```
minholdestrainc1g,minholdtempc1g
(e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3,

6x e10.3, 6x f10.3,6x e10.3, 6x f10.3, 6x e10.3, 6x f10.3 )

*CFOPEN, FEA_CLEANED_N_PSTRAIN_C1,data,,append
*VWRITE, sr, tmt, tmca, re, strain_rate, total_cycles, ang, holdtime,

maxpstrainc1n,maxtempc1n,maxholdpstrainc1n,maxholdtempc1n, minpstrainc1n,mintempc1n,

minholdpstrainc1n,minholdtempc1n
(e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3,

6x e10.3, 6x f10.3,6x e10.3, 6x f10.3, 6x e10.3, 6x f10.3 )

*CFOPEN, FEA_CLEANED_G_PSTRAIN_C1,data,,append
*VWRITE, sr, tmt, tmca, re, strain_rate, total_cycles, ang, holdtime,

maxpstrainc1g,maxtempc1g,maxholdpstrainc1g,maxholdtempc1g, minpstrainc1g,mintempc1g,

minholdpstrainc1g,minholdtempc1g
(e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3,

6x e10.3, 6x f10.3,6x e10.3, 6x f10.3, 6x e10.3, 6x f10.3 )

*CFOPEN, FEA_CLEANED_N_CSTRAIN_C1,data,,append
*VWRITE, sr, tmt, tmca, re, strain_rate, total_cycles, ang, holdtime,

maxcstrainc1n,maxtempc1n,maxholdcstrainc1n,maxholdtempc1n, mincstrainc1n,mintempc1n,

minholdcstrainc1n,minholdtempc1n
(e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3,

6x e10.3, 6x f10.3,6x e10.3, 6x f10.3, 6x e10.3, 6x f10.4 )

*CFOPEN, FEA_CLEANED_G_CSTRAIN_C1,data,,append
*VWRITE, sr, tmt, tmca, re, strain_rate, total_cycles, ang, holdtime,

maxcstrainc1g,maxtempc1g,maxholdcstrainc1g,maxholdtempc1g, mincstrainc1g,mintempc1g,

minholdcstrainc1g,minholdtempc1g
(e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3,

6x e10.3, 6x f10.3,6x e10.3, 6x f10.3, 6x e10.3, 6x f10.4 )

*CFOPEN, FEA_CLEANED_N_TSTRAIN_C1,data,,append
```

```
*VWRITE, sr, tmt, tmca, re, strain_rate, total_cycles, ang, holdtime,

maxtstrainc1n,maxtempc1n,maxholdtstrainc1n,maxholdtempc1n, mintstrainc1n,mintempc1n,

minholdtstrainc1n,minholdtempc1n
(e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3,

6x e10.3, 6x f10.3,6x e10.3, 6x f10.3, 6x e10.3, 6x f10.4 )

*CFOPEN, FEA_CLEANED_G_TSTRAIN_C1,data,,append
*VWRITE, sr, tmt, tmca, re, strain_rate, total_cycles, ang, holdtime,

maxtstrainc1g,maxtempc1g,maxholdtstrainc1g,maxholdtempc1g, mintstrainc1g,mintempc1g,

minholdtstrainc1g,minholdtempc1g
(e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3,

6x e10.3, 6x f10.3,6x e10.3, 6x f10.3, 6x e10.3, 6x f10.4 )

*CFOPEN, FEA_CLEANED_N_STRESS_C2,data,,append
*VWRITE, sr, tmt, tmca, re, strain_rate, total_cycles, ang, holdtime,

maxstressc2n,maxtempc2n,maxholdstressc2n,maxholdtempc2n, minstressc2n,mintempc2n,

minholdstressc2n,minholdtempc2n
(e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x f10.3,

6x f10.3, 6x f10.3,6x f10.3, 6x f10.3, 6x f10.3, 6x f10.3 )

*CFOPEN, FEA_CLEANED_G_STRESS_C2,data,,append
*VWRITE, sr, tmt, tmca, re, strain_rate, total_cycles, ang, holdtime,

maxstressc2g,maxtempc2g,maxholdstressc2g,maxholdtempc2g, minstressc2g,mintempc2g,

minholdstressc2g,minholdtempc2g
(e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x f10.3,

6x f10.3, 6x f10.3,6x f10.3, 6x f10.3, 6x f10.3, 6x f10.3 )

*CFOPEN, FEA_CLEANED_N_ESTRAIN_C2,data,,append
*VWRITE, sr, tmt, tmca, re, strain_rate, total_cycles, ang, holdtime,

maxestrainc2n,maxtempc2n,maxholdestrainc2n,maxholdtempc2n, minestrainc2n,mintempc2n,

minholdestrainc2n,minholdtempc2n
```

```
(e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3,

6x e10.3, 6x f10.3,6x e10.3, 6x f10.3, 6x e10.3, 6x f10.3 )

*CFOPEN, FEA_CLEANED_G_ESTRAIN_C2,data,,append
*VWRITE, sr, tmt, tmca, re, strain_rate, total_cycles, ang, holdtime,

maxestrainc2g,maxtempc2g,maxholdestrainc2g,maxholdtempc2g, minestrainc2g,mintempc2g,

minholdestrainc2g,minholdtempc2g
(e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3,

6x e10.3, 6x f10.3,6x e10.3, 6x f10.3, 6x e10.3, 6x f10.3 )

*CFOPEN, FEA_CLEANED_N_PSTRAIN_C2,data,,append
*VWRITE, sr, tmt, tmca, re, strain_rate, total_cycles, ang, holdtime,

maxpstrainc2n,maxtempc2n,maxholdpstrainc2n,maxholdtempc2n, minpstrainc2n,mintempc2n,

minholdpstrainc2n,minholdtempc2n
(e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3,

6x e10.3, 6x f10.3,6x e10.3, 6x f10.3, 6x e10.3, 6x f10.3 )

*CFOPEN, FEA_CLEANED_G_PSTRAIN_C2,data,,append
*VWRITE, sr, tmt, tmca, re, strain_rate, total_cycles, ang, holdtime,

maxpstrainc2g,maxtempc2g,maxholdpstrainc2g,maxholdtempc2g, minpstrainc2g,mintempc2g,

minholdpstrainc2g,minholdtempc2g
(e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3,

6x e10.3, 6x f10.3,6x e10.3, 6x f10.3, 6x e10.3, 6x f10.3 )

*CFOPEN, FEA_CLEANED_N_CSTRAIN_C2,data,,append
*VWRITE, sr, tmt, tmca, re, strain_rate, total_cycles, ang, holdtime,

maxcstrainc2n,maxtempc2n,maxholdcstrainc2n,maxholdtempc2n, mincstrainc2n,mintempc2n,

minholdcstrainc2n,minholdtempc2n
(e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3,

6x e10.3, 6x f10.3,6x e10.3, 6x f10.3, 6x e10.3, 6x f10.4 )

*CFOPEN, FEA_CLEANED_G_CSTRAIN_C2,data,,append
```

```
*VWRITE, sr, tmt, tmca, re, strain_rate, total_cycles, ang, holdtime,

maxcstrainc2g,maxtempc2g,maxholdcstrainc2g,maxholdtempc2g, mincstrainc2g,mintempc2g,

minholdcstrainc2g,minholdtempc2g
(e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3,

6x e10.3, 6x f10.3,6x e10.3, 6x f10.3, 6x e10.3, 6x f10.4 )

*CFOPEN, FEA_CLEANED_N_TSTRAIN_C2,data,,append
*VWRITE, sr, tmt, tmca, re, strain_rate, total_cycles, ang, holdtime,

maxtstrainc2n,maxtempc2n,maxholdtstrainc2n,maxholdtempc2n, mintstrainc2n,mintempc2n,

minholdtstrainc2n,minholdtempc2n
(e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3,

6x e10.3, 6x f10.3,6x e10.3, 6x f10.3, 6x e10.3, 6x f10.4 )

*CFOPEN, FEA_CLEANED_G_TSTRAIN_C2,data,,append
*VWRITE, sr, tmt, tmca, re, strain_rate, total_cycles, ang, holdtime,

maxtstrainc2g,maxtempc2g,maxholdtstrainc2g,maxholdtempc2g, mintstrainc2g,mintempc2g,

minholdtstrainc2g,minholdtempc2g
(e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3,

6x e10.3, 6x f10.3,6x e10.3, 6x f10.3, 6x e10.3, 6x f10.4 )

*CFOPEN, FEA_CLEANED_N_STRESS_C3,data,,append
*VWRITE, sr, tmt, tmca, re, strain_rate, total_cycles, ang, holdtime,

maxstressc3n,maxtempc3n,maxholdstressc3n,maxholdtempc3n, minstressc3n,mintempc3n,

minholdstressc3n,minholdtempc3n
(e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x f10.3,

6x f10.3, 6x f10.3,6x f10.3, 6x f10.3, 6x f10.3, 6x f10.3 )

*CFOPEN, FEA_CLEANED_G_STRESS_C3,data,,append
*VWRITE, sr, tmt, tmca, re, strain_rate, total_cycles, ang, holdtime,

maxstressc3g,maxtempc3g,maxholdstressc3g,maxholdtempc3g, minstressc3g,mintempc3g,

minholdstressc3g,minholdtempc3g
```

```
(e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x f10.3,

6x f10.3, 6x f10.3,6x f10.3, 6x f10.3, 6x f10.3, 6x f10.3 )

*CFOPEN, FEA_CLEANED_N_ESTRAIN_C3,data,,append
*VWRITE, sr, tmt, tmca, re, strain_rate, total_cycles, ang, holdtime,

maxestrainc3n,maxtempc3n,maxholdestrainc3n,maxholdtempc3n, minestrainc3n,mintempc3n,

minholdestrainc3n,minholdtempc3n
(e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3,

6x e10.3, 6x f10.3,6x e10.3, 6x f10.3, 6x e10.3, 6x f10.3 )

*CFOPEN, FEA_CLEANED_G_ESTRAIN_C3,data,,append
*VWRITE, sr, tmt, tmca, re, strain_rate, total_cycles, ang, holdtime,

maxestrainc3g,maxtempc3g,maxholdestrainc3g,maxholdtempc3g, minestrainc3g,mintempc3g,

minholdestrainc3g,minholdtempc3g
(e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3,

6x e10.3, 6x f10.3,6x e10.3, 6x f10.3, 6x e10.3, 6x f10.3 )

*CFOPEN, FEA_CLEANED_N_PSTRAIN_C3,data,,append
*VWRITE, sr, tmt, tmca, re, strain_rate, total_cycles, ang, holdtime,

maxpstrainc3n,maxtempc3n,maxholdpstrainc3n,maxholdtempc3n, minpstrainc3n,mintempc3n,

minholdpstrainc3n,minholdtempc3n
(e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3,

6x e10.3, 6x f10.3,6x e10.3, 6x f10.3, 6x e10.3, 6x f10.3 )

*CFOPEN, FEA_CLEANED_G_PSTRAIN_C3,data,,append
*VWRITE, sr, tmt, tmca, re, strain_rate, total_cycles, ang, holdtime,

maxpstrainc3g,maxtempc3g,maxholdpstrainc3g,maxholdtempc3g, minpstrainc3g,mintempc3g,

minholdpstrainc3g,minholdtempc3g
(e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3,

6x e10.3, 6x f10.3,6x e10.3, 6x f10.3, 6x e10.3, 6x f10.3 )

*CFOPEN, FEA_CLEANED_N_CSTRAIN_C3,data,,append
```

```
*VWRITE, sr, tmt, tmca, re, strain_rate, total_cycles, ang, holdtime,

maxcstrainc3n,maxtempc3n,maxholdcstrainc3n,maxholdtempc3n, mincstrainc3n,mintempc3n,

minholdcstrainc3n,minholdtempc3n
(e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3,

6x e10.3, 6x f10.3,6x e10.3, 6x f10.3, 6x e10.3, 6x f10.4 )

*CFOPEN, FEA_CLEANED_G_CSTRAIN_C3,data,,append
*VWRITE, sr, tmt, tmca, re, strain_rate, total_cycles, ang, holdtime,

maxcstrainc3g,maxtempc3g,maxholdcstrainc3g,maxholdtempc3g, mincstrainc3g,mintempc3g,

minholdcstrainc3g,minholdtempc3g
(e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3,

6x e10.3, 6x f10.3,6x e10.3, 6x f10.3, 6x e10.3, 6x f10.4 )

*CFOPEN, FEA_CLEANED_N_TSTRAIN_C3,data,,append
*VWRITE, sr, tmt, tmca, re, strain_rate, total_cycles, ang, holdtime,

maxtstrainc3n,maxtempc3n,maxholdtstrainc3n,maxholdtempc3n, mintstrainc3n,mintempc3n,

minholdtstrainc3n,minholdtempc3n
(e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3,

6x e10.3, 6x f10.3,6x e10.3, 6x f10.3, 6x e10.3, 6x f10.4 )

*CFOPEN, FEA_CLEANED_G_TSTRAIN_C3,data,,append
*VWRITE, sr, tmt, tmca, re, strain_rate, total_cycles, ang, holdtime,

maxtstrainc3g,maxtempc3g,maxholdtstrainc3g,maxholdtempc3g, mintstrainc3g,mintempc3g,

minholdtstrainc3g,minholdtempc3g
(e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3,

6x e10.3, 6x f10.3,6x e10.3, 6x f10.3, 6x e10.3, 6x f10.4 )

*CFOPEN, FEA_CLEANED_SUM_C1,data,,append
*VWRITE, sr, tmt, tmca, re, strain_rate, total_cycles, ang, holdtime,

maxtstrainc1n,maxtempc1n,maxtstrainc1g,maxtempc1g, maxstressc1n,maxtempc1n,

maxstressc1g,maxtempc1g
```

```
(e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3,

6x e10.3, 6x f10.3,6x e10.3, 6x f10.3, 6x e10.3, 6x f10.4 )

*CFOPEN, FEA_CLEANED_SUM_C2,data,,append
*VWRITE, sr, tmt, tmca, re, strain_rate, total_cycles, ang, holdtime,

maxtstrainc2n,maxtempc2n,maxtstrainc2g,maxtempc2g, maxstressc2n,maxtempc2n,

maxstressc2g,maxtempc2g
(e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3, 6x f10.3, 6x f10.3, 6x e10.3, 6x f10.3,

6x e10.3, 6x f10.3,6x e10.3, 6x f10.3, 6x e10.3, 6x f10.4 )

/OUTPUT, FEA_Junk22,txt

!*****************************************************************************
**

! Parametric Simulation Termination

I=I+1
FINISH
*ENDDO
*ENDDO
*ENDDO
*ENDDO
*ENDDO
```