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Life Fraction Hardening Applied to a Modified Theta Projection Creep Model for a Nickel-based Super-alloy

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ABSTRACT

This paper presents the application of a life fraction hardening rule to the analytical calculation of creep in hot section components. Accurate prediction of creep is critical to assuring the mechanical integrity of heavy-duty, industrial gas turbine (IGT) hardware. The accuracy of such predictions depend upon both the creep models assumed and how those models are implemented in a finite element solution. A modified theta projection creep model for a nickel-based super alloy was presented in a previous paper as an accurate simulation of creep behavior [1]. Application of such a user defined creep law depends upon definition of a hardening rule in the form of either an explicit or an implicit integration scheme in order to calculate incremental strains during any time increment. Time hardening is the simplest and least computationally intensive of the two most common hardening rules, but does not correctly show the effect of changing stresses or temperatures. Strain hardening may provide the most accurate solution, but the creep models are too complex to invert, which results in highly iterative and computationally intensive solutions. A life fraction hardening rule has been presented in other works [2] as a compromise between time hardening and strain hardening. Life fraction hardening is presented here as a highly efficient and accurate means of calculating incremental creep strain when applied to a modified theta projection creep model. A user creep subroutine was defined using a state variable to represent the strain life fraction at any time. By using the time to tertiary creep as the denominator for the life fraction, no new material constants are needed to relate to creep failure. The start of tertiary creep is effectively considered to be a failure. Additional design insight can be provided through the inclusion of other state variables to calculate temperature margins at current conditions. Material testing with changing stress levels will be used to help validate the technique. A simplified example of the technique is presented in the paper. More accurate creep predictions allow our company to improve the structural integrity of its turbine blades and vanes.

1. INTRODUCTION

When turbine blades are subjected to centrifugal loading, thermal stresses and high temperatures, creep creates voids which eventually link to form cracks [3]. The components are subjected to a multiaxial state of stress where every point in the part experiences varying stress and temperature levels. Over time, some portions of the component experience stress relaxation and others are relentlessly loaded. The mechanical integrity of state-of-the-art turbine and combustor hardware depend upon the accurate prediction of creep and stress rupture behavior. This requires substantial material testing [4], accurate creep models [5], and a robust creep analysis scheme that includes a definition of failure [6]. The aim of this paper is to present robust creep analysis technique for calculating accumulated creep strain in the presence of changing stresses and/or temperatures.

An earlier paper demonstrated how a modified theta projection (MTP) creep model could be used to accurately predict the three phases of creep over a range of temperatures and stress conditions [1]. The equation for the original theta projection model contained only two terms [7]. This necessarily limited the TPM's ability to completely match the shape of a complete curve. Furthermore, there is no definition of failure in the TPM model. The creep equation will predict increasing levels of strain but not indicate that a failure has occurred. Huge strains could be predicted with no indication of failure unless the user defines a “cut-off” or failure strain as shown in [6].

$$\varepsilon_c = \left(\varepsilon_{pri} + \varepsilon_{\sec} + \varepsilon_{ter}\right) \tag{1}$$

For the MTP model, each phase is simulated with a separate term (1), to represent the phases shown in figure 1.

Initially, a MTP model was generated for a proprietary, nickel-based, equiaxed, super alloy used in turbine blades. Subsequently, a second model was made for another nickel-based alloy used in turbine vanes. The identity of these materials is withheld and material information is normalized due to the proprietary nature of the information. These models could directly be used to predict creep behavior for relentless, non-relaxing, loading. In components where stresses are permitted to relax, the creep model must be incorporated in a finite element solution to incrementally calculate strain accumulation and stress relaxation over time. The application of a user-defined creep law depends upon the definition of a hardening rule to determine how incremental strain will be calculated in the present of a changing stress field. The MTP model is readily used with a life fraction hardening rule to accurately and efficiently predict incremental creep strain. The time to the beginning of tertiary creep provides an excellent reference for calculation of a life fraction. This paper will describe the implementation of a user creep subroutine which uses a state variable to represent the strain life fraction at any time increment. An additional state variable is used to estimate the temperature margin to tertiary creep at any given location.

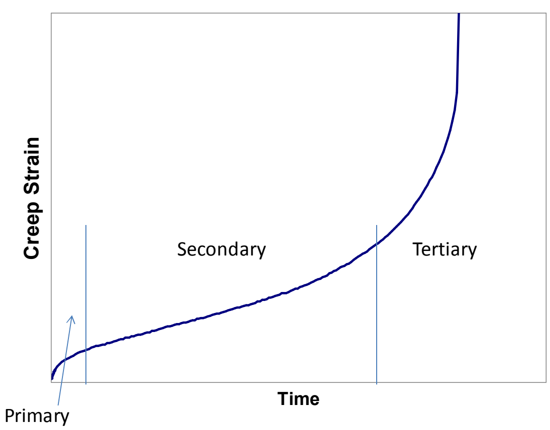

Figure 1. Typical Creep Deformation Curve

2. NOMENCLATURE

A, A_i	Constant Coefficient for Theta (i) fit
B, B_i	Stress Coefficient for Theta (i) fit
C, C_i	Temperature Coefficient for Theta (i) fit
D, D_i	Coupling Coefficient for Theta (i) fit
ELF	Strain Life Fraction
f	failure
i	index denoting individual thetas
LMP	Larson Miller Parameter
MTP	Modified Theta Projection
OEM	Original Engine Manufacturer
S	Stress
t	Time (hrs)
t^*	Effective Time
t_f	Time at Failure
t_{pri}	Primary Creep Characteristic Time
$t_{\sec}$	Secondary Creep Characteristic Time
t_{ter}	Tertiary Creep Start Time
T	Temperature
T_{base}	Baseline Temperature
T_{Design}	Design Temperature
T_{Mar}	Temperature Margin
T_{MELT}	Incipient Melting Temperature
T_O	Threshold Temperature
ΔT	Temperature Margin
ε_c	Creep Strain (in %)
$\dot{\varepsilon}_c$	Creep Strain Rate (in %/hr)
ε_{pri}	Primary Creep Strain Term (in %)
$\varepsilon_{\sec}$	Secondary Creep Strain Term (in %)
ε_{ter}	Tertiary Creep Strain Term (in %)
ε_1	Maximum Primary Creep Strain (in %)
$\dot{\varepsilon}_2$	Secondary Creep Strain Rate (in %/hr)
σ	Equivalent Stress
σ_{Design}	Design Stress
σ_o	Creep Threshold Stress
σ_{yield}	Yield Stress
θ	Material Theta Coefficient

3. MODIFIED THETA PROJECTION MODEL

The theta projection creep model [2] was developed to provide a global creep model that depicts all phases of creep with only two terms. However, it has limited ability to predict the onset of tertiary creep or accurately predict the acceleration of secondary creep. The modified theta projection, MTP, model was created to overcome this limitation. The MTP model also fits the first and second derivative of creep as shown in figure 2. Instead of a cut-off strain, the MTP can use the on-set of tertiary creep as a slightly conservative failure condition.

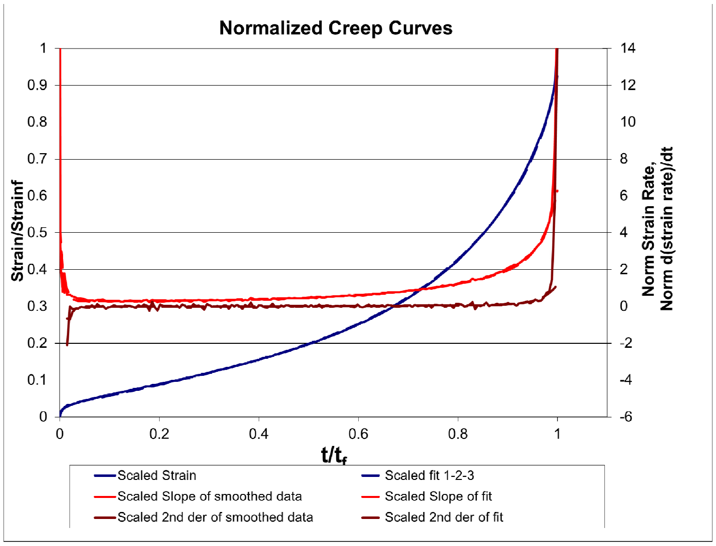

Figure 2. All Phases Modeled

A separate term was used for each phase of creep (2)-(4) and an overall scaling factor (5) ensured that zero stress resulted in zero creep. The theta constants are arranged in such a way that they represent physically meaningful quantities such as characteristic times, creep rates, or primary strains shown in the (b) form of each equation. The primary creep characteristic time is chosen to represent the best fit of the creep deceleration seen during primary creep.

Primary Creep

$$\varepsilon_{pri} = \theta_3\left[1-e^{-t/\theta_1}\right]\theta_8 \tag{2a}$$

$$\varepsilon_{pri} = \varepsilon_1\left[1-e^{-t/t_{pri}}\right]\theta_8 \tag{2b}$$

The secondary creep characteristic time represents the time at which the secondary creep rate has accelerated 20% beyond the minimum value (hence the 5e in equation 3b).

Secondary Creep

$$\varepsilon_{\sec} = \theta_4\left[t+\frac{\theta_2}{5e}\left(e^{t/\theta_2}-1\right)\right]\theta_8 \tag{3a}$$

$$\varepsilon_{\sec} = \dot{\varepsilon}_2\left[t+\frac{t_{\sec}}{5e}\left(e^{t/t_{\sec}}-1\right)\right]\theta_8 \tag{3b}$$

The tertiary creep is the least important component other than the time at which it initiates. The onset of tertiary creep occurs when the creep increases more that .05% beyond the value predicted from the secondary creep term.

Tertiary Creep

$$\varepsilon_{ter} = \theta_7\frac{t}{\theta_5}e^{\theta_6\left(t/\theta_5-1\right)}\theta_8 \tag{4a}$$

$$\varepsilon_{ter} = .05\frac{t}{t_{ter}}e^{\theta_6\left(t/t_{ter}-1\right)}\theta_8 \tag{4b}$$

Overall Scaling (Original Form)

$$\theta_8 = \left(1-e^{-\sigma/\sigma_o}\right) \tag{5}$$

Where the threshold stress, defined in (6), was chosen such that it mimicked the behavior of existing net section allowable curves already being used, as shown in Figure 3. The red curve represents a net section stress that would result in particular strain over part life. This allowable was based on a Larson-Miller [8] fit of creep data. The threshold goes to zero when temperature reaches incipient melt. At the incipient melt temperature, in theory zero stress would result in positive creep. The terms in (6) were chosen to fit material behavior without increasing the burden of fitting additional coefficients.

$$\sigma_o = \left[\frac{\left(T_{Melt}-T\right)}{\left(T_{Melt}-T_o\right)}\right]^3\sigma_{yield@T_o} \tag{6}$$

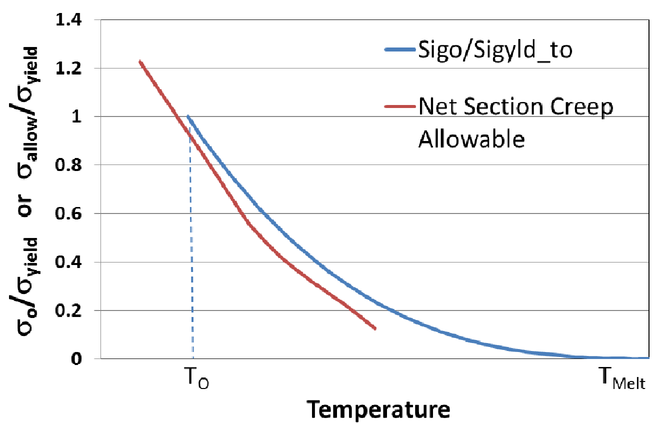

Figure 3. σ_o **Shape and Creep Allowable vs. Temp**

Subsequent to the original publication, it was observed that the θ_8 scaling factor deviated from unity enough to affect the accuracy of the theta values as measurements of physical behavior. Since the sole purpose of this term is to ensure that zero stress has zero creep, a similar equation was needed. An equation was chosen which approaches unity much more rapidly. Figure 4 shows that the new form of θ_8 is nearly 1 at σ_o.

$$\theta_8 * = \tanh(2\sigma / \sigma_o) \quad (7)$$

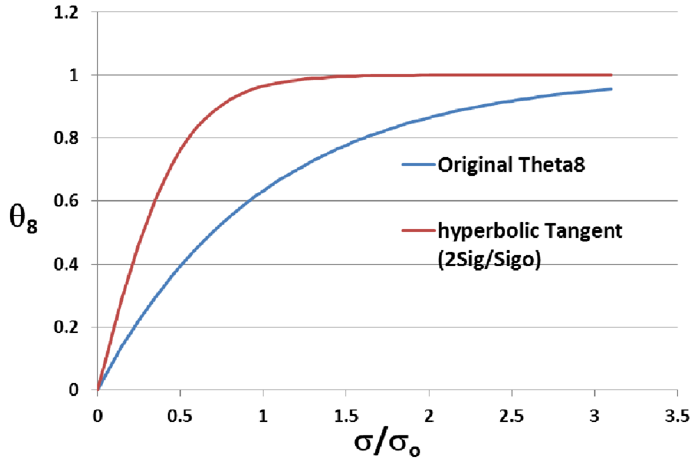

Figure 4. Original and New Scaling Term

While it was very straight forward to precisely fit theta for any individual curve, it was much more difficult to create a global model where the thetas are functions of stress and temperature. Theta is assumed to be either a linear function shown in equation (7), or an exponential one of the form shown in equation (8) based on the Evans Theta projection model[7]. Only the θ_6 term used equation (7).

$$\theta_i = A_i + B_i\sigma + C_iT + D_i\sigma T \quad (7)$$

$$\theta_i = e^{A_i + B_i\sigma + C_iT + D_i\sigma T} \quad (8)$$

4. FITTING OF GLOBAL MODELS

The initial fit of the blade alloy described in [1] was based upon 29 material tests. Material information is withheld and data is normalized due to the proprietary nature of the data. The fitting was repeated with the inclusion of an additional 8 creep specimen tests, and an additional 26 stress rupture test results of specimens made from blades. The stress rupture tests provided the time to failure and a rough estimate of strain at failure, but not a complete creep curve. As previously reported the best theta fits are for theta 1, 2, 4, and 5. Of these thetas, the tertiary time, or theta 5, was the best fit. A comparison or Actual Strain/Predicted Strain is shown in Figure 5 where both results are scaled to the same factors. Examining a set of isothermal curves at varying stress levels, in Figure 6, one observes that the curves are not identical scaling of each other. The strain, at start of tertiary, decreases with increasing stress.

A creep model was fit of a second material using the same automated fitting process that written for in commercially available programming language [9] to find the minimum of constrained nonlinear multivariable function. The second material, a nickel based vane alloy, verified that the MTP model was valid for more than one material. The quality of the fit was similar to that of the blade alloy. A comparison or Actual Strain/Predicted Strain is shown in Figure 7. Once again, the tertiary time was the most precisely fit coefficient.

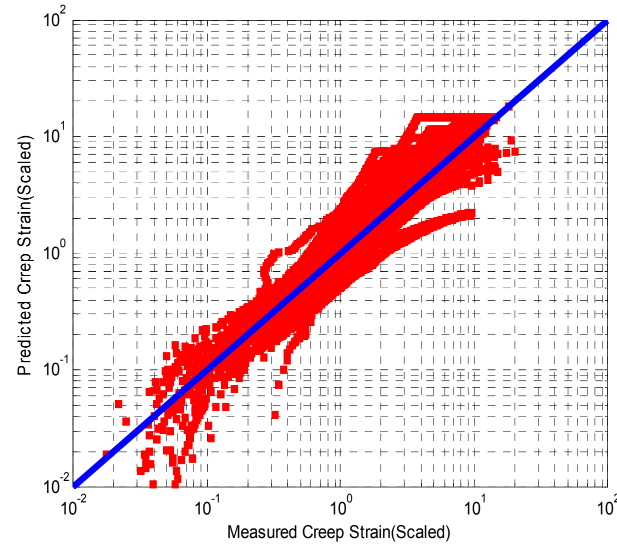

Figure 5. Creep Strain Predicted by MTP vs. Measure Creep Strain for Blade Alloy

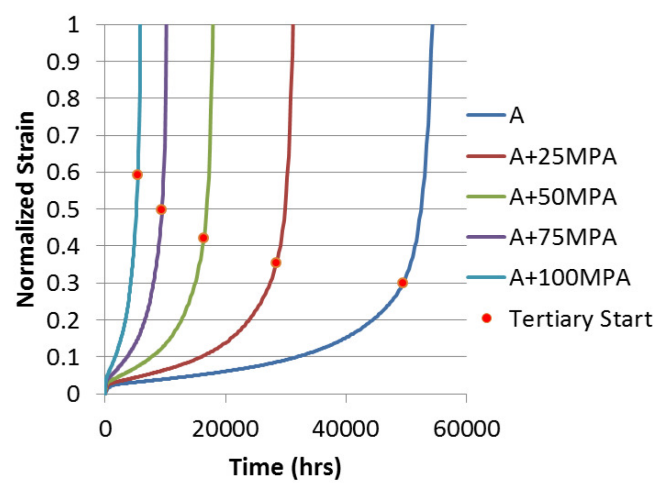

Figure 6. Example Isothermal Creep Curves

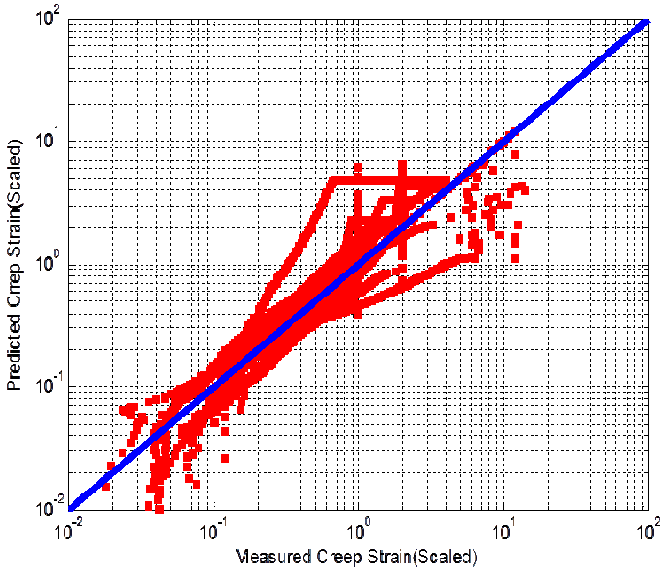

Figure 7. Creep Strain Predicted by MTP vs. Measure Creep Strain for Vane Alloy

Since it is undesirable for a component to reach tertiary creep in normal commercial operation, components should be designed to only operate in primary and secondary creep. By using the start of tertiary creep as the definition of failure a Weibull analysis can be done of the test data to determine what creep life margin is required to ensure a particular probability of failure. By considering the probability distributions of creep behavior other researchers have been able accurately interpolate and extrapolate predicted results [10] for properties with non-normal distributions. Figure 8 shows that a life factor of safety of <2 is required to expect a probability of 1 in 1000.

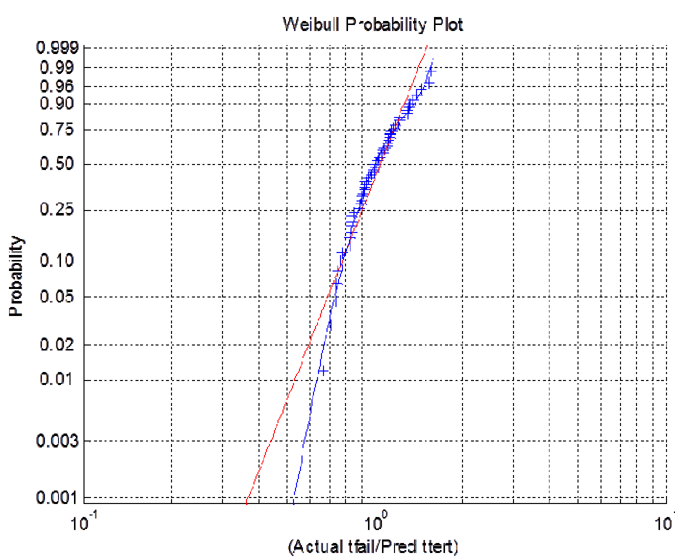

Figure 8. Blade Alloy Weibull Plot of Actual$_{tfail}$ /Pred$_{ttert}$

5. COMPUTATIONAL PREDICTION OF CREEP

Except for situations where loading is relentless, such as a creep test, a model defining creep as a function of stress, time and temperature is insufficient for predicting creep. An assumption must be made as to how creep behavior is affected by the previous load history. In most instances of creep, stresses will relax over time. Application of such a user defined creep law [11] depends upon definition of a hardening rule in the form of either an explicit or an implicit integration scheme in order to calculate incremental strains during any time increment (9).

$$\Delta\varepsilon_c = f(\sigma, T, \Delta t, ?) \qquad (9)$$

Judicious choice of the hardening rule is required to obtain an accurate and efficient solution. Increasing the number of factors a creep model contains not only drives up the difficulty of constant determination. It also makes it more difficult to manipulate equations. The more complex the creep model becomes, the more difficult it is to be both accurate and computationally efficient. The two most common rules are time hardening and strain hardening represent extremes of this issue. A third option, life-fraction hardening, is illustrated in this paper.

6. TIME HARDENING

Time hardening assumes that the incremental strain depends only on time, in addition to stress and temperature as shown in (10).

$$\Delta\varepsilon_c = f(\sigma, T, \Delta t, t) \qquad (10)$$

Time hardening is generally the easiest rule to apply because the user merely needs to be able to calculate the first derivative of creep in order to estimate the incremental creep (11).

$$\dot{\varepsilon}_c = \left(\dot{\varepsilon}_{pri} + \dot{\varepsilon}_{\sec} + \dot{\varepsilon}_{ter}\right) \qquad (11)$$

However, this technique can be extremely non-conservative in the presence of a relaxing stress field. Figure 9 shows an example where stresses are instantaneously reduced by 75MPA after 5000 hrs of running (Point F). Incremental strains continue along the gold curve because the rate comes from point B on the reduced curve. One can observe that the creep life of a part depends more upon how far the stress relaxes than on the damage done during the period with high stress exposure.

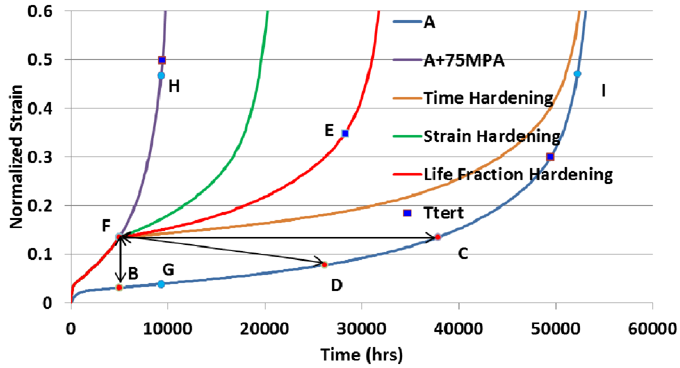

Figure 9. Stress Reduced at 5000Hrs

Conversely, if stress or temperature is increased over time, this method is extremely-conservative. An extreme example of this would be a part exposed to a modest stress and temperature combination for a long time period (9.6khrs at stress level A) would be at point G. Increasing stress 75MPA would move to an incremental creep rate associated with point H. So capability would vanish if a component were then subject to an increase in stress or temperature, through events such as an increased firing temperature or an over-speed. This rate could be high enough to indicate immediate failure.

Time hardening is computationally simple to solve, but inappropriate for most real problems. It would only be suitable for situations where a part is relentlessly loaded with a nearly uniform stress, for example the net section of a later stage turbine blade.

7. STRAIN HARDENING

Strain hardening is more difficult computationally. It assumes that the incremental strain depends on the creep strain, stress and temperature (12). Equations 2 to 5 are not easily inverted in terms of strain. It would be more practical to solve iteratively, but this adds to the computational cost of the solution. Figure 9 shows a strain hardening example, where an instantaneous reduction in stress at point F changes the incremental strain rate to follow along the green curve. The rate values are derived from those at point C onward. The resultant behavior is obviously much more conservative than time hardening.

$$\Delta\varepsilon_c = f(\sigma, T, \Delta t, \varepsilon_c) \qquad (12)$$

While it could be argued that strain hardening is more valid than time hardening, it remains to be proven that it accurately represents material behavior. It would assume that the strain value is more important than whether a component is in primary, secondary or tertiary creep. If one considers a component stressed at level A+75MPA, point H in Figure 9, one observes that a decrease in stress to level A would move the creep rate to that seen at point I. This would indicate a reduction in creep rate, but it occurs in the tertiary creep regime for those conditions.

Testing with either stepped loading or temperatures is needed to validate hardening rules chosen. Reference [1] suggests that the life-fraction hardening rule is the most accurate.

An additional consideration to be made in choosing hardening rule would be how to define failure. Both time hardening and strain hardening would usually consider a limit, or cut-off, creep strain perhaps as a function of temperature. Since tertiary strain is well defined with the MTP model, it would be relatively straight forward to calculate the strain at tertiary creep by substituting in θ_5 for time in (1)-(6); however, this strain value would continually change with stress and temperature. For the previous example, point I already exceeds the strain to tertiary for that stress temperature combination. One cannot use strain at tertiary without assuming that a reduction in stress results in immediate "failure".

8. LIFE FRACTION HARDENING

Life fraction hardening assumes that creep damage can be continually tracked as a fraction of the time to creep failure (13). The life fraction hardening contains elements of the Larson Miller Parameter [8], combined with Robinson's rule for creep damage [12]. Figure 10 shows that plots of the test and predicted LMP, based on tertiary creep start, are consistent with LMP plots typically seen for rupture. Stress in the figure is normalized by a constant and LMP is normalized by the lowest value tested. The constant, *Cons*, is a value between 15 and 25 chosen to collapse the data at different temperatures to a single curve. The LMP in (14) can be rewritten to give the stress as a function of LMP and T in Eq. (15).

$$ELF = \sum_{inc=1}^{n} \frac{\Delta t}{t_{ter}} = \sum_{i=1}^{n} \frac{\Delta t}{\theta_5} \qquad (13)$$

$$LMP = (273.15 + T)(Cons + \log_{10}(\theta_5)) \qquad (14)$$

$$\sigma = \frac{\left[\left(\dfrac{\dfrac{LMP}{273.15+T} - Cons}{\log_{10} e}\right) - A_5 - C_5 T\right]}{B_5 + D_5 T} \qquad (15)$$

Creep damage linearly accumulates based on the time increment divided by the current θ_5. Since θ_5 is a function of stress and temperature, life fraction hardening readily accounts for changes in stress and temperature. The ELF term is directly comparable to the Robinson's rule for linear accumulation of damage (16) except for the use of tertiary creep instead of failure.

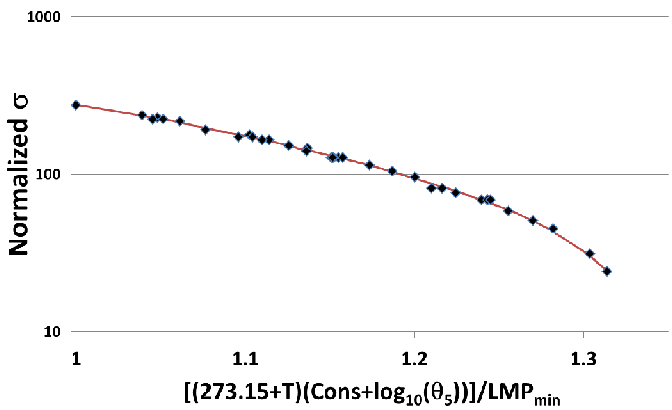

Figure 10. LMP Plot of Time to Tertiary Creep

$$Damage = \sum_{i=1}^{n} \frac{t}{t_{fail}} \tag{16}$$

Since it is undesirable to design a component to reach tertiary creep, it is reasonable to use the time to tertiary creep as the scaling parameter of life. The life fraction can be continually tracked as a state variable in the finite element solution.

At the beginning of every time increment the effective time, t*, is calculated at the current stress and temperature. So the incremental strain becomes a function of stress, temperature, incremental time and the effective time, (17). The incremental strain becomes just a rewrite of the basic MTP equation with effective time used in place of time in (18).

$$t^* = ELF \times \theta_5 \big|_{\sigma,T} \tag{17}$$

$$\Delta\varepsilon_c = f(\sigma, T, \Delta t, t^*) \tag{18}$$

The incremental strain can be determined by taking the derivative of creep strain for each of the 3 creep phases, (19)-(21).

$$\dot{\varepsilon}_{pri} = \frac{\theta_3\theta_8}{\theta_1} e^{-t^*/\theta_1} \tag{19}$$

$$\dot{\varepsilon}_{\sec} = \theta_4\theta_8\left[1 + \frac{1}{5e} e^{t^*/\theta_2}\right] \tag{20}$$

$$\dot{\varepsilon}_{ter} = \frac{\theta_7\theta_8}{\theta_5} e^{\theta_6\left(t^*/\theta_5 - 1\right)}\left(t^*\frac{\theta_6}{\theta_5} + 1\right) \tag{21}$$

If an implicit creep integration scheme is implemented, the partial derivative the incremental creep with respect to the stress is needed. An accurate approximation is made by calculating the change in incremental strain produced by a small increase in stress (22).

$$\partial\Delta\varepsilon_c / \partial\sigma \approx \frac{\left(\Delta\varepsilon_c\big|_{\sigma} - \Delta\varepsilon_c\big|_{1.001\sigma}\right)}{0.001\sigma} \tag{22}$$

Figure 9 shows an example of life fraction hardening where the instantaneous reduction in stress at point F changes the incremental strain to follow along the red curve. The rate values are derived from those at point D onward. It is observed that it may be considered a compromise position between strain hardening and time hardening. Validation testing is being planned. An ideal testing scenario would be it incrementally increase stress or temperature on a daily basis an plot the resultant creep.

A more common scenario to expect would be for the stress to gradually relax over time. Figure 11 shows an example where stress is reduced by 25MPa every 2000hrs from Stress level A+100MPa to A. A full red circle denotes the time point at which each load drop occurs. One sees that time hardening is dominated by the low stress value and strain hardening is dominated by the high stress value. Life fraction hardening produces a result in between the two extremes.

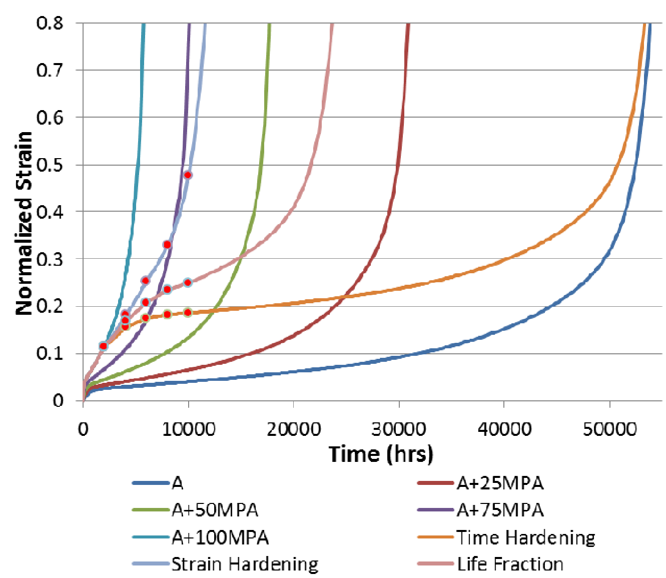

Figure 11. Stress Reduced Every 2000hrs

9. TEMPERATURE MARGIN

While the aero-thermal and durability engineers have an interest in the creep deflection of a component and reassurance that the part will not fail, they are more interested in the thermal margins. Being able to readily see how much increased temperature a part can withstand (or how much temperature must be reduced to meet requirements), even if it is an estimate, would be a valuable tool for the analyst. By making some simplifying assumptions a temperature margin can be calculated at any point in the analysis. The temperature margin would be defined as that magnitude of the temperature increase which would have resulted in tertiary creep (ELF=1) being reached at a given time.

A simplifying assumption is made that the relaxation of stress does not significantly change the temperature margin. A second assumption would be that the stress does not relax any further due to the increased temperature. Tracking the ELF at any time and knowing the time at tertiary stress, (23) provides a simple estimate for what value of tertiary time would be required to increase ELF to unity.

$$ELF \times \theta_5\Big|_{Tbase} \cong 1 \times \theta_5\Big|_{Tbase+Tmar} \qquad (23)$$

Based on (8), one can see that the baseline value of theta 5 cancels out of (24) leaving the simple equation (25) as an estimate of temperature margin.

$$ELF \times \theta_5\Big|_{Tbase} \cong \theta_5\Big|_{Tbase} e^{C_8 T_{Mar} + D_8 \sigma T_{Mar}} \qquad (24)$$

$$T_{mar} = \ln(ELF) \Big/ \left(C_8 + D_8\sigma\right) \qquad (25)$$

The presence of stress in (25) makes it clear that if stress changes over the load history, it will affect the margin. The margin will be correct only for relentless load situations where stress does not change. Figure 12, shows an example of a case where stress in decreased at 5000hours. A plot of creep assuming strain hardening is shown with plots of constant load creep at A and A+75MPa. The prediction of T_{mar} is plotted relative to the secondary axis vs time. As an accuracy check, the predicted strain assuming 5000hrs at stress A+75MPa and 5000hrs at A with temperature raised to $T+T_{mar}$ was plotted in Gold. In this particular case the tertiary creep strain, point F, is reached at 9400hrs instead of the predicted value of 10000hrs. Strain at 10,000hrs is about 8% higher than tertiary start. This non-conservative result was because of constant D in equation (25) will result in temperature margin changing if stress is not constant. However if the additional temperature allows the stress to relax further, the prediction rapidly becomes conservative. Only a decrease of stress of 0.15% is needed to make the predictions match.

It should be emphasized that the scatter of the material data must be considered when calculating the temperature margin. The FEA analysis should be run out to a time greater than required to compensate for material scatter. Based on Figure 8, the model should be run to about 2X required life to provide a .001 probability of failure. Temperature margin should be evaluated including this factor.

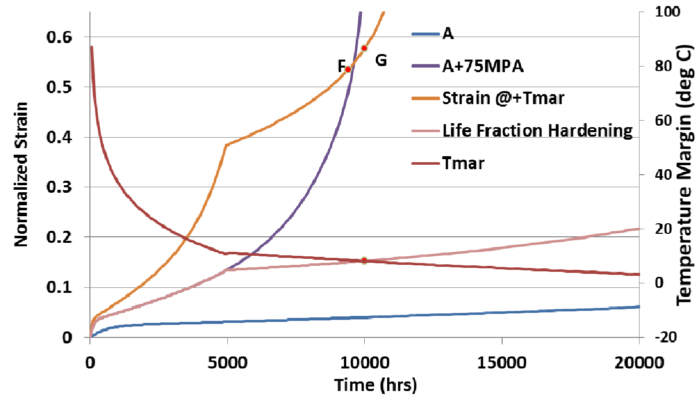

Figure 12. Comparison to Strain at Tbase+Tmar

10. LIFE FRACTION POST PROCESSING

Post processing of a creep analysis would usually consist of plots of creep strain, deformed shape, and permanent deflection. Figure 13 shows an example creep analysis where the MTP model and life fraction hardening has been applied. There is nothing that would automatically indicate an issue to the analyst, unless they were cognizant of a strain or deflection limit. These plots only represent an example of a creep analysis using the life fraction hardening and MTP, and are not intended to show specific FEA modeling practice or modeling sensitivity.

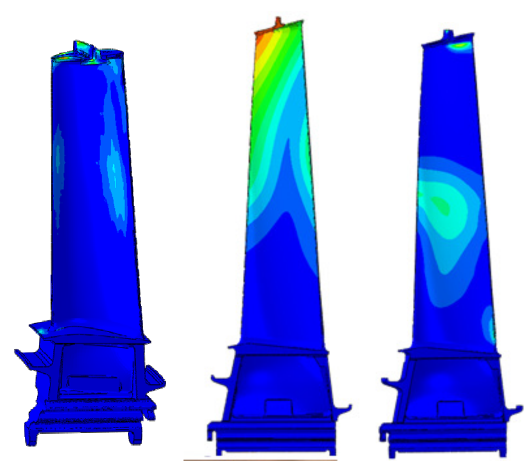

Figure 13. Creep Strain, Deformation, Permanent Deflection

Since the life fraction is tracked as a state variable during the solution, it is readily available for plotting purposes. The analyst may find it more useful to plot the life fraction since it is a reasonable prediction of the percentage of total life consumed. Plots of T_{mar} would also be of interest to quickly tell designers where component temperature could be increased or decreased for a more efficient design. Figure 14, shows a plot to temperature margin at an example location. This location cracks with an OEM material and geometry, but has adequate margin with PSM materials and geometry.

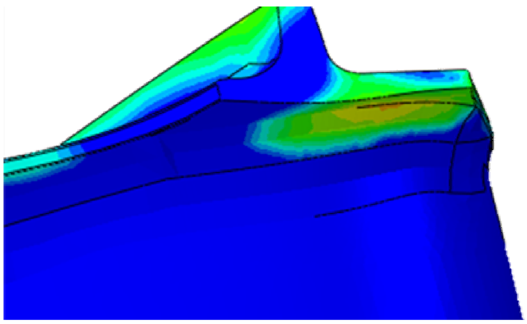

Figure 14. T_{mar} Plot Identifying Min Margin Location

11. CONCLUSIONS

Life fraction hardening is a viable method for calculating incremental creep in a non-relentlessly loaded component. It is less computationally intensive method of calculation than strain hardening. It is less non-conservative than time hardening. The modified theta projection creep model is particularly suited for application of a life fraction hardening rule because it includes a value for the start of tertiary creep which provides an appropriate value to measure life fraction against. The time to tertiary creep had the best fit of all the creep values for the two materials analyzed. Based on the scatter experienced in testing a life safety factor of less than 2 is required to provide a B0.1 probability of failure. This assumes only material scatter and no scatter in load or temperature. The use of MTP and life fraction hardening also permits the analyst to predict temperature margin to tertiary creep. Temperature margin plotting quickly identifies location where geometry or cooling schemes should be modified to improve life or component efficiency. Additional testing is required to validate that life fraction hardening accurately represents the effects of varying stresses and temperature on creep accumulation. More accurate creep predictions allow our company to improve the structural integrity of its turbine blades and vanes.

12. REFERENCES

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