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Creep behaviour of Waspaloy under non-constant stress and temperature

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Creep behaviour of Waspaloy under non-constant stress and temperature

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Abstract

Current creep models are derived using data from constant stress (or load) creep tests and are capable of accurately predicting creep behaviour when applied conditions are constant or near constant. However, analyses of creep curve shapes for the nickel based superalloy Waspaloy, when applied stress and/or temperature vary greatly during testing, have shown that predictive methods based purely on strain, time or life-fraction are insufficient and cannot predict observed creep rates. This is important when considering stress concentration features where stress relaxation due to creep can significantly alter the distribution of stress and thus affect fatigue life.

When both stress and temperature are changed during a creep test, dislocation movement must proceed through a dislocation network formed under different conditions, resulting in greater than expected creep rates. It is proposed that this is due to a reduction in effective internal stress due to changes in dislocation structure.

Keywords

Creep, Superalloy, Stress-Relaxation, Hardening Rules, Dislocation Creep

Introduction

Due to the high temperatures and stresses in the rotating turbine components in a gas-turbine, the effects of creep must be well understood. These components are designed to operate within safe limits based on an understanding of material behaviour obtained from testing and microstructural observations. The creep models used for design purposes are mostly derived from constant stress (or load) creep tests and are capable of accurately predicting creep behaviour when applied conditions are constant or near constant. However, in many cases the stress and/or temperature may vary significantly during service, for example during stress relaxation, around a fatigue crack at high temperature or during thermo-mechanical fatigue. In pure metals, dislocation movement is hindered by dislocation-dislocation interactions and interactions with grain boundaries or precipitates. Stress change creep experiments in pure metals and some alloys[1,2,3,4] have shown that upon a modest stress drop, creep rates are initially low since the dislocation substructure does not change rapidly and the dislocations must now move through a dislocation substructure formed at higher stress. Since all dislocations have an associated stress field and the dislocation substructures may have a very inhomogeneous density, the internal stress across a material may vary greatly[5].

Waspaloy is an example of a wrought nickel-based superalloy, a family of alloys which perform a key role in gas turbine aero engines due to their superior mechanical properties at elevated temperatures and good corrosion resistance. This high temperature strength is usually provided by a distribution of γô (Ni_3Al, Ni_3Ti) precipitates which obstruct dislocation movement. The nature of the interactions of dislocations with the γô varies depending on applied conditions and each precipitate has an associated effect on the surrounding internal stress[6].

Experimental Procedure

Constant and non-constant stress creep tests were conducted on the wrought nickel-based superalloy Waspaloy. The tests were carried out using Andrade-Chalmers constant stress cam creep machines and test conditions were chosen to give lives of approximately 10 days based on existing test data for Waspaloy[7]. The test conditions used for the constant stress and temperature creep tests are given in table 1.

Table 1: Stress and temperature for constant stress creep tests on Waspaloy.

Temperature (°C)	Stress (MPa)
550	1060
600	880
650	690
700	540
750	390

Tensile creep tests with non-constant stress and temperature were also conducted. These tests were performed using the same procedure as the constant stress tests, however the test conditions were varied between 2 pairs of values show in table 1 in 24 hour and 120 hour intervals. When both stress and temperature were changed during a test, a transition period of 1 hour was used to allow temperature to stabilise to a new level. During this period the stress was held at the lower of the old and new values to avoid excessive creep damage during this period.

Experimental Results

Normal uniaxial constant stress creep curves were obtained for Waspaloy for each of the applied conditions (Fig 1) with a transition in primary dominated creep for the high stress/low temperature to a tertiary dominated creep curve for the low stress/high temperature tests.

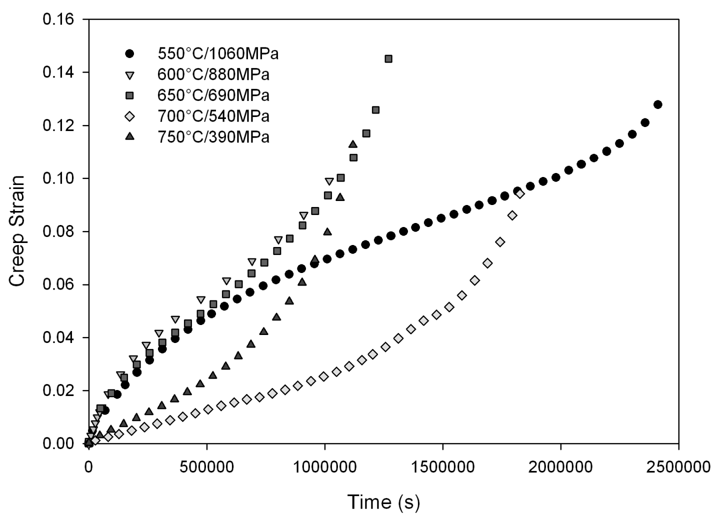

Figure 1: Constant stress creep curves for Waspaloy.

When test conditions were changed during a test the initial creep rate immediately subsequent to the application of new condition, the creep rate was faster than expected based on constant stress data at those conditions. However the rate rapidly decreases, resulting in a period of ópseudoô primary creep after each load/temperature change. An example of this can be seen in Fig. 2 which shows the creep rate obtained from a Waspaloy creep test where the temperature/stress change from 600°C/880MPa to 750°C/390MPa every 24hrs. Creep rates obtained from the non-constant stress/temperature tests are consistently higher than those obtained at constant stress and test lives are only fractionally shorter. Therefore the failure strains tend to be higher than those obtained for constant stress. A longer interval was used to allow the creep rate to stabilise after changing the test conditions. Fig. 3 shows the creep rate obtained from a creep test where the temperature/stress changes from 650°C/690MPa to 750°C/390MPa every 120hrs. This plot shows the strain rate initially decreasing following a change in test conditions followed by an increase in rate as tertiary creep becomes dominant.

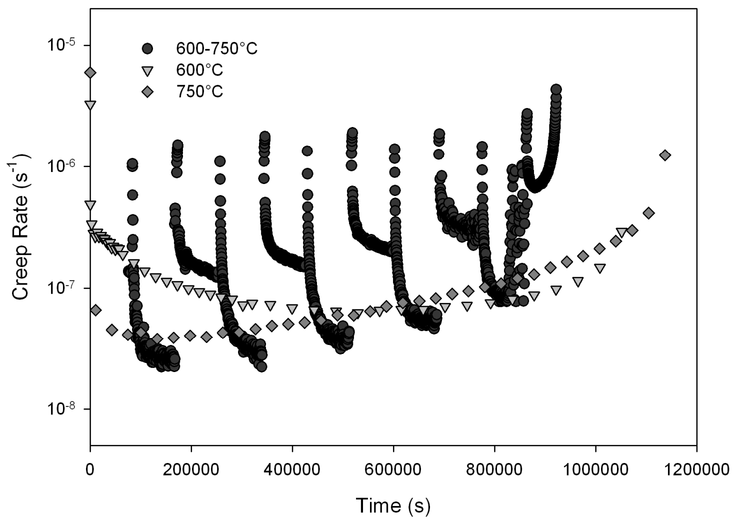

Figure 2: Creep rates obtained from a uniaxial creep test where the temperature/stress are cycled between 600°C/880MPa to 750°C/390MPa every 24hrs and those obtained at constant temperature/stress.

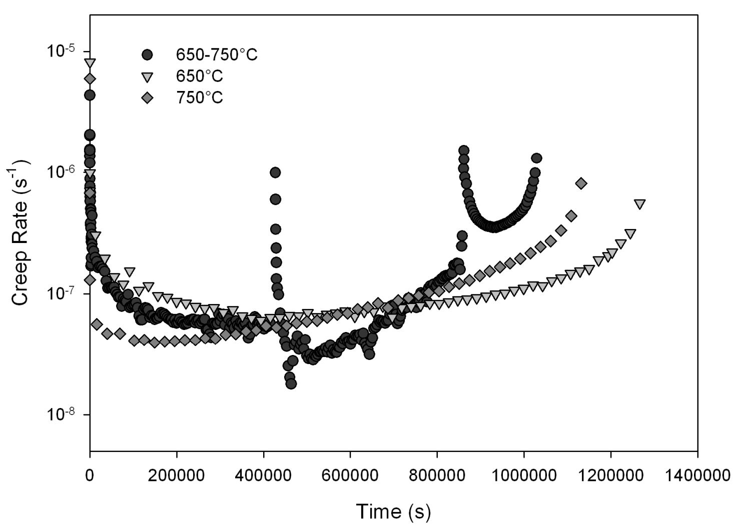

Figure 3: Creep rates obtained from a uniaxial creep test where the temperature/stress are cycled between 650°C/690MPa to 750°C/390MPa every 120hrs and those obtained at constant temperature/stress.

Modelling

To facilitate predicting creep rates over the duration of a test a numerical representation of the creep curve has been used. The θ-projection method was used since it accurately represents the full shape of the creep curve. θ values obtained for each of the constant stress creep test are shown in table 2. No attempt has been made to relate these values to applied test conditions.

$$\varepsilon_t = \theta_1\left(1 - e^{-\theta_2 t}\right) + \theta_3\left(e^{\theta_4 t} - 1\right) \quad \text{é} \quad (1)$$

Table 2: θ-values for Waspaloy constant stress creep curves.

Stress (MPa)	Temperature (°C)	θ_1	θ_2	θ_3	θ_4
1060	550	0.046535	3.17E-06	0.086632	2.47E-07
880	600	0.030746	8.41E-06	0.049679	8.25E-07
690	650	0.030973	7.43E-06	0.019123	1.44E-06
540	700	0.006059	5.15E-06	0.006014	1.44E-06
390	750	0.017909	2.38E-06	0.003484	2.92E-06

An important aspect of modelling creep behaviour is accounting for prior creep deformation. Time, strain and life-fraction based hardening methods are often used to quantify the effects of prior creep on strain rate (Fig. 4). Time hardening is the simplest concept where creep rate is calculated based on the creep rate at time equal to the total analysis time on a creep curve at applied stress/temperature. This method is rarely used when there are large changes in applied stress. The strain hardening model is more suitable in instances where the stress varies considerably during an analysis, however, this method may produce inaccuracies if the conditions vary from those displaying a primary dominated creep curve to those displaying a tertiary dominated creep curve or vice versa. Life-fraction hardening attempts to address this issue by calculating creep rate based on effective time, equal to the analysis time (t) divided by rupture time (t_F) at the analysis conditions. This method has the advantage of predicting creep rupture when t/t_F equals 1.

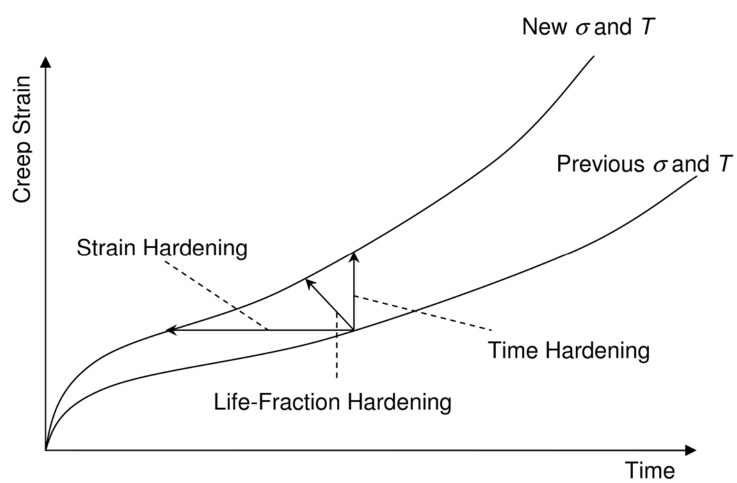

Figure 4: Schematic representation of strain hardening, time hardening and life-fraction hardening during a change in creep conditions.

An alternative method is to predict hardening based on internal state variables used to represent micromechanical processes that occur during creep. An approach developed by Evans [8] assumes that primary creep is due to competing dislocation hardening and recovery mechanisms which may or may not interact with one another and that tertiary creep is due to long-range structure deterioration and various damage mechanisms. The sums of the various dislocation hardening, recovery and damage mechanisms may be quantified by the parameters *H*, *R* and *W* respectively. Creep rate may then be calculated

$$\dot{\varepsilon} = \dot{\varepsilon}_0 \left(1 + H + R + W\right) \tag{2}$$

where $\dot{\varepsilon}_0$ is the initial effective creep rate for the virgin material. The hardening, recovery and damage variables *H*, *R* and *W* accumulate with time and strain by

$$\dot{H} = -H'\dot{\varepsilon}, \qquad \dot{R} = R', \qquad \dot{W} = W'\dot{\varepsilon} \tag{3}$$

where H', R' and W' are functions of stress and temperature. These parameters, along with $\dot{\varepsilon}_0$ can be calculated from the creep curve using:

$$\dot{\varepsilon}_0 \equiv \theta_1\theta_2 + \theta_3\theta_4, \qquad H' \equiv \frac{\theta_2}{\theta_1\theta_2 + \theta_3\theta_4}, \qquad R' \equiv \frac{\theta_2\theta_3\theta_4}{\theta_1\theta_2 + \theta_3\theta_4}, \qquad W' \equiv \frac{1}{\theta_3} \tag{4}$$

The methods outlined above have been used to predict creep rates of Waspaloy under non-constant stress and temperature (Fig. 5). For each method, the θ-values were used depending on the applied test conditions. The predicted creep rates for both time and life-fraction hardening were similar since test conditions were chosen to give similar lives for each constant stress test. Both of these methods under predicted the change in creep rate due to the change in test conditions. The strain hardening model produced very poor predictions with predicted strain rates increasing when transitioning from high stress/low temperature to low stress/high temperature conditions while the experimental results showed a significant decrease in rate. The hardening method based on internal state variables produces the best predictions with creep rates increasing and decreasing with similar magnitudes to those observed experimentally with changing test conditions. However, none of the hardening models predict the 'pseudo' primary creep on changing test conditions.

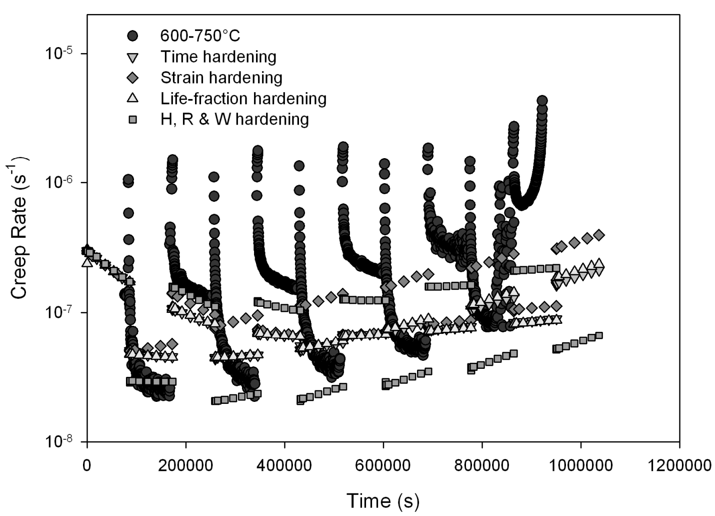

Figure 5: Predicted and experimentally obtained creep rates from a uniaxial creep test with a temperature/stress changing between 600°C/880MPa and 750°C/390MPa every 24hrs.

Discussion

The difference in creep curve shape observed in Fig. 1 indicates that different creep mechanisms are dominant for the high and low stress tests. The high stress/low temperature tests were conducted above yield stress and hence accumulated plastic strain prior to creep. Therefore, creep proceeded in a work-hardening dislocation structure and the creep curve exhibits significant primary creep. The high temperature/low stress creep tests were performed at stresses below yield and the creep curves are tertiary dominated.

When stress and temperature were both changed during an experiment the creep rate immediately after the change was much faster that expected, however this rate soon dropped to a level close to that expected for the applied conditions. This results in a period of pseudo primary creep after each stress and temperature change. This can be attributed to the dislocations moving through a dislocation network form at different applied conditions. Furthermore, at high stress dislocations overcome ɔô by cutting where as at low stress dislocations overcome ɔô by diffusion controlled climb[6]. Therefore, dislocations held up at ɔôat low stress may be freed by cutting with an increase in stress and those restricted at high stress may become mobile due to climb with an increase in temperature thus increasing creep rate immediately following a stress and/or temperature change.

The results of the modelling indicate that calculating creep rate based purely on total strain or time produces unrealistic predictions. The difference in creep curve shape observed for the different constant stress tests is not quantified in these simple methods. However, the constitutive method based on material state variables representing micromechanical phenomenon produces better predictions since the strain accumulated by primary creep effects is detached from tertiary creep effects.

Conclusions

- When using creep data for component design, the effects of varying stress and temperature must be considered.
- Creep tests performed on Waspaloy with varying stress and temperature show that creep rates are faster than expected when test conditions are changed.
- Traditional hardening approaches such as time and strain hardening produce inaccuracies when creep conditions vary significantly.
- A creep hardening model based on internal state variables produces more accurate prediction under non-constant stress and temperature.

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