Constructing a Validated Deformation Mechanism Map using Low Temperature Creep Strain Accommodation Processes for Nickel-Base Alloy 718

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Abstract

A creep Deformation Mechanism Map (DMM) of an engineering alloy can be an effective tool for developing physics-based prognostics systems. Long term creep testing and analysis of complex engineering alloys has shown that power law breakdown phenomenon is related to the dominance of Grain Boundary Sliding (GBS) as opposed to diffusion creep.

A DMM is constructed for a fine grained Alloy 718 and is validated by comparison with a collection of experimental data obtained from the literature. The GBS accommodated by wedge type cracking is considered dominant at low temperatures (0.3 to 0.5 T_m i.e. melting temperature in Kelvin) whereas GBS accommodated by creep dominates above 0.55 T_m.

Introduction

Alloy 718 is widely used in the industry for high temperature applications in aircraft as well as land-based gas turbine engines with creep strain accumulation and formation of a creep crack as the main design criteria used in practice for this class of materials.

The creep deformation is a time dependent and thermally activated plastic strain accumulation process controlled by the competition between the activation energies associated with different mechanisms. The constitutive equations for creep define creep strain-rate as a function of applied stress, temperature and material microstructure:

$$\frac{d\varepsilon}{dt} = f(\sigma_t, T_t, S_t)$$

A creep DMM is a diagram that plots normalized stress and temperature and divided the two dimensional stress and temperature space into different regions in which a specific deformation mechanism remains dominant.

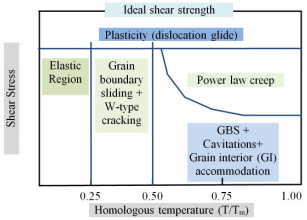

Figure 1: The most recent modification of DMM [1]

Methodology

Part 1 : Data Collection

An extensive literature survey was conducted to collect as much creep data as possible. The construction of a practical DMM using numerical techniques requires the availability of experimental data over a wide range of temperature and loading conditions. The data collection exercise focused on the minimum creep rate which is the most critical design parameter that can be extracted from a constant load creep test from a life prediction perspective. Values for creep strain rates were plotted for tests performed on samples with a grain size of approximately 10 µm. Generally, each deformation mechanism leads to a different value of the stress exponent (n) in the Arrhenius-type creep equation.

Part 2 : Computational Model for DMM

A frequently-used model for creep strain rate around the power-law break-down is the superposition of two strains coming from Grain Boundary Sliding (GBS) and Intra-Granular (IG) deformation (or dislocation climb). The constant coefficient and power values have been modified to obtain a better agreement with the experimental data. The model uses temperature dependant Diffusion and Shear modulus terms.

$$\dot{\varepsilon} = \dot{\varepsilon}_{gbs} + \dot{\varepsilon}_{ig}$$

$$\dot{\varepsilon}_{gbs} = 10^{10} D_{gbs} \frac{Gb}{kT}\left(\frac{b}{d}\right)^2\left(\frac{\sigma}{G}\right)^2 \qquad D_{gbs} = D_{0c}\exp\left(\frac{-Q_c}{RT}\right)$$

$$\dot{\varepsilon}_{ig} = 8\times 10^{13} D_{ig} \frac{Gb}{kT}\left(\frac{\sigma-\sigma_0}{G}\right)^7 \qquad D_{ig} = D_{0v}\exp\left(\frac{-Q_v}{RT}\right)$$

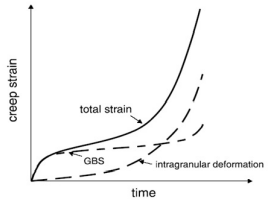

Figure 1: Superposition creep model around the power-law break-down region [2]

Table 1: Values employed in computation algorithm

Parameter	Notation	Value	Unit
Melting Temperature	T_m	1600	$^\circ K$
Burger Vector	b	2.5×10^{-4}	μm
Boltzman Constant	k	1.38×10^{-23}	$J/^\circ K$
Pre-exponent, Intragranular	D_{0v}	2×10^{-6}	m^2/s
Activation Energy, Intragranular	Q_v	425000	J/mol
Gas Constant	R	8.3144	$J/mol^\circ K$
Grain Size	d	30	μm
Friction Stress	σ_0	22×10^6	Pa
Pre-exponent, gbs	D_{0gbs}	$4b^2D_{0v}$	m^2/s
Activation Energy, gbs	Q_{gbs}	$0.6Q_v$	J/mol

Results and Discussion

The slope of the trend lines added to the ORNL experimental data [3] suggests a modification to the n-power values in rate equations such that the n-power is now 7 for the intra-granular rate equation (dislocation climb). The constant coefficient has also been adjusted for these equations and is equal to 8 x 10^{13} for the intra-granular rate equation and 10^{10} for the grain boundary sliding rate equation in order to develop a better prediction compared to the experimental data.

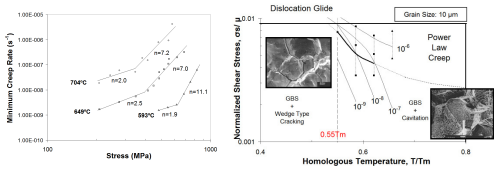

Figure 2: Plot of minimum creep rate vs. stress showing the power-law breakdown at various temperatures [3] and experimentally developed boundary between GBS and PL.

Fig. 3 presents a 4D contour plot that visualizes two rate contours together. This helps understand the contribution from each mechanism to the total rate shown in Fig. 4. This shows also the boundary between two mechanisms. The intersections between the black contours (GBS rate) and color contours (intra-granular / climb) demonstrate the boundary between two mechanisms where the dominant mechanism switches from one to the other.

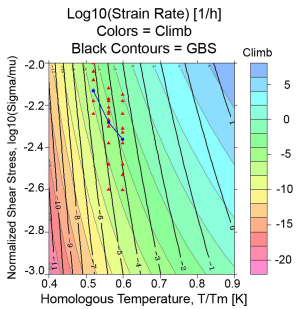

Figure 3: 4D Contour plot that visualizes two rate contours at the same time for comparison between the contributions from each mechanism

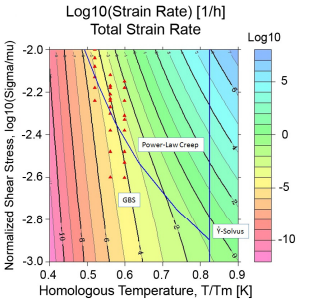

Figure 4: Computational DMM developed and compared to the experimental data from Oak Ridge National Laboratory

A comparison between the computationally developed DMM and experimental data obtained from the literature indicates that the creep rates for Alloy 718 can be properly predicted .

Conclusion and Future Work

A rationale and a methodology for developing practical Ashby type Deformation Mechanism Map has been created. Unlike traditional Ashby type DMM where diffusion creep is considered dominant at lower stresses and temperatures, GBS is considered to be the dominant deformation mechanisms below the Power Law breakdown point as a function of stress and temperature.

This DMM can be used for creep life predictions of Alloy 718 in ranges of temperatures and stresses used in practical applications, as well as to design experimental creep test matrices for wider ranges of stresses and temperatures.

Further work will be required to validate the contribution from different grain sizes to the overall creep rate.

References

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