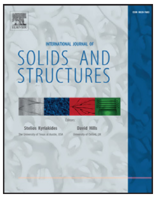
International Journal of Solids and Structures 000 (2018) 1–9

Contents lists available at ScienceDirect

International Journal of Solids and Structures

journal homepage: www.elsevier.com/locate/ijsolstr



Influence of prior cyclic plasticity on creep deformation using crystal plasticity modelling

T.O. Erinosho*, K. Abburi Venkata, M. Mostafavi, D.M. Knowles, C.E. Truman

Solid Mechanics Group, Department of Mechanical Engineering, University of Bristol, Bristol BS8 1TR, UK

ARTICLE INFO

Article history:
Received 25 September 2017
Revised 14 January 2018
Available online xxx

Keywords:
Crystal plasticity
Creep
Fatigue
Prior plasticity
Finite element analysis

ABSTRACT

This paper proposes a simple, yet effective, modified crystal plasticity framework which is capable of modelling plasticity and creep deformation. In particular, the proposed model is sufficiently versatile to capture the effects of complex load histories on polycrystals, representative of those experienced by real materials in industrial plant. Specifically, the methodology was motivated by the need in the power generation industry to determine whether cyclic pre-straining influences the subsequent creep behaviour of type 316H austenitic stainless steel as compared to non-cyclically pre-strained material. Cyclic pre-straining occurs widely in plant and it is of paramount importance to accurately account for its impact on the subsequent deformation and integrity of relevant components.

The framework proposed in this paper considers the effects of dislocation glide and climb in a relatively simple manner. It is calibrated using experimental tests on 316H stainless steel subjected solely to monotonic plasticity and forward creep. Predictions are then obtained for the creep response of the same material after it had been subjected to cycles of pre-strain. The predictions are compared to experimental results and good agreement was observed. The results show slower creep strain accumulation following prior cyclic loading attributed to hardening structures developed in the material during the cyclic pre-strain. The model also highlights the importance of accounting for directionality of hardening under reverse loading. This is hypothesized to affect the development of an internal stress state at an intragranular level which is likely to affect subsequent creep accumulation.

1. Introduction

This paper proposes a plasticity and creep deformation model within a crystal plasticity finite element framework and uses it to investigate the influence of cyclic pre-strain on creep in type 316H stainless steel. The behaviour of stainless steel in various creep regimes has been extensively reported in the literature due to its wide range of applications in the power generation industry (Mehmanparast et al., 2016; Mehmanparast et al., 2013; Hong et al., 2016). Creep in metals is defined as time-dependent permanent deformation which occurs under an applied stress typically when the temperature (T) exceed $0.5T_m$, where T_m is the melting temperature of the metal (Edward and Ashby, 1979). In dislocation creep, the high temperature and stress provide the energy required for immobilized dislocations to climb to a coplanar slip plane, thus overcoming the obstacles due to dislocation traps such as jogs/kinks or precipitates. The resulting climb assisted glide leads to time-dependent permanent deformations known as creep deformation (Weertman, 1955).

Studies have shown that the dislocation creep response of a component is influenced by its prior plastic loading history (Mehmanparast et al., 2016; Mikami, 2016; Marnier et al., 2016; Joseph et al., 2013; Esztergar, 1972; Wei and Dyson, 1982). However, the significance of the influence of monotonic/cyclic pre-straining remains uncertain and has been debated (Joseph et al., 2013). Wei and Dyson (1982) observed that higher plastic pre-straining of 316 stainless steel, up to 1.5% tensile strain, increases its subsequent creep life. Hong et al. (2016) experiments on 347 stainless steel showed that monotonically pre-straining samples up to 30% plastic strain at 650 °C and then applying stresses greater than 200 MPa increases its creep life compared to lower levels of pre-straining. They attributed this behaviour to the formation of twinning due to the high pre-existing deformation which acts as a barrier to dislocation glide. Conversely, low levels of pre-strain accelerate strain-induced precipitation of sigma phases at grain boundaries that act at sites of creep cav-

---

* Corresponding author.
E-mail address: tomiwa.erinosho@bristol.ac.uk (T.O. Erinosho).

https://doi.org/10.1016/j.ijsolstr.2018.01.028

Please cite this article as: T.O. Erinosho et al., Influence of prior cyclic plasticity on creep deformation using crystal plasticity modelling, International Journal of Solids and Structures (2018), https://doi.org/10.1016/j.ijsolstr.2018.01.028

Nomenclature

All quantities are dimensionless unless otherwise stated

$\boldsymbol{F}$	total deformation gradient
$\boldsymbol{F^p}$	plastic deformation gradient
$\boldsymbol{F^e}$	elastic deformation gradient
$\boldsymbol{I}$	identity Matrix
$\boldsymbol{\gamma^\alpha}$	slip on slip system $\boldsymbol{\alpha}$ ($\mathbf{s}^{-1}$)
$\boldsymbol{n^\alpha}$	slip plane $\boldsymbol{\alpha}$
$\boldsymbol{s^\alpha}$	slip direction $\boldsymbol{\alpha}$
$\boldsymbol{L^p}$	plastic velocity gradient
$\boldsymbol{\Omega^p}$	spin
$\boldsymbol{\dot{\gamma}^\alpha}$	alip rate on slip system $\boldsymbol{\alpha}$
$\boldsymbol{D^p}$	symmetric part of velocity gradient
$\boldsymbol{\Omega^e}$	asymmetric part of velocity gradient
$\boldsymbol{\dot{\gamma}_0}$	reference slip rate ($\mathbf{s}^{-1}$)
$\boldsymbol{\tau^\alpha}$	shear stress on slip system $\boldsymbol{\alpha}$
$\boldsymbol{h_0}$	hardening modulus (Pa)
$\boldsymbol{g^\alpha}$	slip strength on slip system $\boldsymbol{\alpha}$
ҕ	dislocation climb softening factor
$\boldsymbol{\gamma_{sum}}$	accumulated slip
$\boldsymbol{\sigma_{vm}}$	Von Mises stress (Pa)
$\boldsymbol{\psi}$	activation energy (J)
$\boldsymbol{k}$	Boltzmann constant ($\mathbf{m^2kgs^{-2}K^{-1}}$)
$\boldsymbol{T}$	temperature (K)
$\boldsymbol{T_m}$	melting temperature (K)
$\Delta\boldsymbol{\varepsilon}$	strain range
$\boldsymbol{N_{slip}}$	number of slip systems
$\boldsymbol{\tau_0}$	critical resolved shear stress (Pa)
$\boldsymbol{\varepsilon_{max}}$	maximum applied strain
$\boldsymbol{\varepsilon_{min}}$	minimum applied strain

ity formation and therefore reduce the tertiary stage of creep life. Murakami et al. (1990) reported that the creep life of type 316 stainless steel is reduced when it is subjected to cyclic pre-straining. Joseph et al. (2013) observed a factor between two and six for the increase in creep life (at 550 °C) of samples which had experienced pre-straining. Mikami's (2016) conclusion that cyclic pre-straining reduces creep life at 650 °C were reconfirmed by Skelton RP (1999) and Takahashi (2015).

The review above reveals that there is considerable uncertainty in evaluating the influence of prior plastic strain on the creep deformation of materials. Experimental complexities associated with the details of loading or unloading during the transition to creep are rarely reported in the literature and could have a profound effect on the measured results. For example, pre-straining in tension or compression, or at high or room temperature prior to creep is likely to influence the nature of creep strain accumulation. Considering the long-term duration of creep experiments, carrying out a comprehensive systematic experimental study to investigate the effects of key parameters on the creep deformation of critical components in the energy industry would be prohibitively costly and time consuming. Details associated with the transition between plasticity and creep in experiments, as well as the wide range of non-proportional strain paths that may be explored, makes a systematic experimental study unfeasible. There is therefore a paramount need to develop a mechanistic model which can correctly simulate the effects of various initial conditions, such as non-proportional straining, on the creep deformation of materials.

Attempts have been made to develop continuum and microstructure-based creep models (Agarwal et al., 2007; Dunne and Hayhurst, 2016; Manonukul et al., 2002; Dunne et al., 1990; Venkatramani et al., 2007; Li et al., 2014; Golden et al., 2014). Studies such as Agarwal et al. (2007), Bower and Wininger (2004) and Dyson (2000) have developed detailed continuum creep deformation and damage models implemented into finite element methods to evaluate the constitutive response of polycrystals during high temperature loading. However, traditional continuum approaches are limited in their ability to account for the influence of local variations at the intragranular scale, such as the distribution of internal stress which is crucial to processes such as creep (Chen et al., 2014). Internal stress here is generally defined as the grain level intergranular orientation dependent stresses developed within the polycrystal model (Roters et al., 2010). Within the grains a distinct internal (intragranular) stress may evolve as a function of the underlying deformation constitutive relations. During creep, stress redistribution will depend on the local crystallographic orientation of that particular grain as well as the incompatibility between neighbouring grains (Pommier et al., 2016). The incompatibility component is typically accounted for in continuum approaches such as self-consistent models (SCM) using a backstress implemented into the constitutive equation, thereby accounting for long range stresses (Hu et al., 2016). This approach provides insights into the influence of kinematic effects on the yield surface evolution.

Given the inability to capture intragranular details in SCM, the crystal plasticity creep framework developed in this paper pursues a discretized finite element approach. This has the advantage of accounting for material microstructure and texture as well as capturing the locally acting mechanisms that drive deformation glide and climb of dislocations. Two approaches may be followed:

(a) Incorporate equations governing the dislocation climb motion into a framework which already describes the dislocation glide, i.e. plasticity. This approach is usually adopted within frameworks that directly simulate the dislocation motion such as discrete dislocation dynamics (Keralavarma et al., 2012; Danas and Deshpande, 2013). Such simulation techniques, although mechanistic, are often limited to modelling simple geometries. However, attempts have been made to implement climb assisted glide motions into higher length-scale modelling frameworks such as crystal plasticity (Geers et al., 2014). Such models require detailed analysis of the microstructure evolution and are often dependent on model calibrations using in-situ or ex-situ microstructural characterization of small scale creep tests.

(b) Rather than directly incorporating the dislocation climb equations in the simulation formulation, it is possible to model climb assisted glide by introducing softening terms within the framework. This approach accommodates relaxation processes which also consider mechanistic aspects of overcoming dislocation traps. It can readily be adopted in a crystal plasticity framework that is capable of simulating thousands of grains in components with complex geometries. Examples of this approach are described in Li et al. (2014) and Hu and Cocks (2016).

The aim of this paper is to develop a modelling framework that captures the effects of prior cyclic plastic strain on the primary and secondary stages of creep deformation. To achieve this, the previous experimental results which will be used to calibrate and validate our model are presented in Section 2 followed by a description of the creep-enabled crystal plasticity (CP) framework in Section 3. The framework is calibrated in Section 4 and in Section 5 the framework is used to determine the influence of prior cyclic plasticity on creep deformation. Discussions on the performance of the current model are presented in Section 6 and finally conclusions are drawn in Section 7.

Please cite this article as: T.O. Erinosho et al., Influence of prior cyclic plasticity on creep deformation using crystal plasticity modelling, International Journal of Solids and Structures (2018), https://doi.org/10.1016/j.ijsolstr.2018.01.028