Computational Materials Science 115 (2016) 26–40

Contents lists available at ScienceDirect

Computational Materials Science

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

Analyzing time- and temperature dependent responses of NARloy-Z

Ruyue Song [a], Anastasia H. Muliana [a,*], Anthony Palazotto [b]

[a] Department of Mechanical Engineering, Texas A&M University, USA
[b] Department of Aeronautics and Astronautics, Air Force Institute of Technology AFIT, USA

A R T I C L E I N F O

Article history:
Received 3 September 2015
Received in revised form 12 November 2015
Accepted 7 December 2015
Available online 2 February 2016

Keywords:
Creep
Alloys
High temperatures
Hysteresis
Energy dissipation
Fatigue

A B S T R A C T

In this study, we investigate the mechanical responses of copper based alloy, NARloy-Z, under cyclic loadings at different strain rates and strain amplitudes, and also creep at different levels of stresses. We examine the effect of temperature changes, as a result of energy dissipation during loading, on the overall cyclic and creep responses of NARloy-Z. A phenomenological viscoplastic model, developed by Freed et al. (1994), is adopted and modified in order to incorporate the effect of energy dissipation on the viscoplastic response of NARloy-Z. An adiabatic process is assumed to convert the dissipated energy into temperature increase, and the resulting temperature changes alter the elastic modulus and plastic flow of NARloy-Z during loading. A numerical method is also presented in order to implement the above nonlinear constitutive model. Experimental data reported by Conway et al. (1975) for cyclic loading and Ellis and Michal (1996) for creep loading are used to examine the viscoplastic responses of NARloy-Z. From the analyses, it is concluded that the amount of energy dissipation is much more pronounced under cyclic loading, especially for long-term duration of cyclic loading, while it is negligible under creep loading. Higher strain rates result in higher energy dissipation, which is expected as higher strain rates accumulate more hysteretic cycles at the same loading duration. Large amount of energy dissipation leads to a pronounced stress softening behavior due to significant increases in temperatures. The stress softening is one of the sources for material failures. It is also seen that the energy dissipation, and its corresponding temperature increase, is an important component in determining fatigue failure of NARloy-Z.

1. Introduction

Many structural components, such as rocket engines and nuclear reactors, are exposed to high temperatures during their services. Thus, they require materials that can operate at elevated temperatures, such as ceramics, metals, or alloys. When subjected to mechanical loadings at high temperatures, metals and alloys exhibit time-dependent and inelastic responses, i.e., creep and plastic deformations (see for example [17,27,13]. Creep responses in metals and alloys at high temperatures are typically classified into primary (transient), secondary (steady-state), and tertiary creep stages based on the rates of creep strains. In the primary stage, the strain rate decreases with time and approaches a constant rate at the steady-state stage. Continuously loading the materials would accelerate the creep strain with an increasing rate (tertiary stage) and ultimately lead to failure. Increasing temperatures and stresses results in early failure of the metals. In many applications, materials are also subjected to more complex loading histories such as cyclic loadings at different amplitude and frequencies that could lead to fatigue failures. Experimental studies on cyclic behaviors in metals and alloys at high temperatures show that fatigue failures depend not only on the amplitude of loading but also on the frequencies (rates) of loadings (see for example [6,22,28]. The frequency- (rate-) dependent fatigue failure in metals at high temperatures is expected which is associated to the prominent creep (time-dependent) material responses at high temperatures.

Materials that experience creep and plastic deformations are considered as dissipative materials since during creep and inelastic deformations, these materials dissipate energy, which in some part is converted into heat. Depending on the magnitude, duration, and condition of loading prescribed to the materials, creep and inelastic deformations can induce significant temperature increases, and mechanical properties of materials often depend on temperatures. Thus, temperature changes due to the energy dissipation can have a significant effect on the overall responses of materials. Experimental observation on cyclic loadings of metals and alloys at room temperatures indicates noticeable temperature increases in the materials due to cyclic loadings. Temperature increases are even higher as the number of cycles increases.

* Corresponding author.
E-mail address: amuliana@tamu.edu (A.H. Muliana).

http://dx.doi.org/10.1016/j.commatsci.2015.12.005
0927-0256/

Nomenclature

μ shear modulus, mega newton per meters square $\left(\frac{MN}{m^2}\right)$
μ_o initial shear modulus at 300 K, mega newton per meters square $\left(\frac{MN}{m^2}\right)$
μ_1 temperature dependence of modulus, mega newton per meters square per kelvin $\left(\frac{MN}{m^2 K}\right)$
T temperature, degree kelvin (K)
k Boltzmann constant, joules per degree kelvin $\left(\frac{J}{K}\right)$
κ bulk modulus, mega newton per meters square $\left(\frac{MN}{m^2}\right)$
E Young's modulus, mega newton per meters square $\left(\frac{MN}{m^2}\right)$
ν Poisson's ratio, dimensionless
α thermal expansion coefficient, one over degree kelvin (K^{-1})
ΔT temperature change, degree kelvin (K)
h hardening modulus, mega newton per meters square $\left(\frac{MN}{m^2}\right)$
l material parameter which determines the stress range for hysteresis loops, dimensionless
f parameter that determines the shape of the hysteresis loop, dimensionless
D_o initial drag strength, mega newton per meters square $\left(\frac{MN}{m^2}\right)$
C stress at which the power law breaks down, mega newton per meters square $\left(\frac{MN}{m^2}\right)$
T_t transition temperature, degree kelvin (K)
$\|\dot{\varepsilon}^p\|_f$ approximate fastest plastic strain rate, one over second $\left(\frac{1}{s}\right)$
$\|\dot{\varepsilon}^p\|_s$ approximate slowest plastic strain rate, one over second $\left(\frac{1}{s}\right)$
$\|\dot{\varepsilon}^p\|_a$ average strain rate, one over second $\left(\frac{1}{s}\right)$
ρ density, kilogram per meters cube (kg/m^3)
c specific heat, joules per kilogram per degree kelvin $\left(\frac{J}{kg\ K}\right)$

There have been several constitutive models developed for describing creep and cyclic behaviors of metals and alloys at high temperatures. Some of these models incorporated the effect of microstructural changes (diffusional transport by dislocation, dislocation climb and glide, grain boundary sliding, etc.) in formulating the macroscopic constitutive materials models. Examples of such models can be found in Amin et al. [1], Sherby and Weertman [26], Frost et al. [11], Gabb and Welsch [12], Orlova [21], etc. The softening and time-dependent behaviors of metals at high temperatures are associated to the dislocation behaviors. Experimental investigations reported by He et al. [15] showed different dislocation configurations of alloys, recorded from the transmission electron microscopy (TEM), at different creep stages. Yue and Lu [28] have examined that fatigue behaviors in superalloy depends on the crystallographic orientation and strain amplitude. They formulated an empirical model including the effect of crystallographic orientations and slip systems on the elastic modulus and plastic hardening parameter in predicting fatigue failure in materials. Phenomenological viscoplastic constitutive models have also been formulated and used to describe creep and cyclic behaviors of metals at high temperatures, e.g., Bodner and Merzer [2], Laflen and Stouffer [18], Lu and Weng [20], Freed et al. [10], among others. Viscoplastic constitutive models have been considered for predicting responses of materials where the effect of time-dependent and inelastic response is prominent. Laflen and Stouffer [18] used a single integral form for capturing time-dependent inelastic deformation in the materials, and this inelastic strain is superposed with the elastic strain in order to determine the total strain in the materials. The models presented by Freed et al. [10] and Lu and Weng [20] considered the influence of time, stress, and temperature on the creep and cyclic responses of metals at elevated temperatures. A plastic strain rate model is defined in terms of the deviatoric stress and activation energy following the Arrhenius function for incorporating the temperature effect. The models were used to simulate steady-state hysteretic responses after a few cycles in alloys under various strain rates and strain amplitude and at different ambient temperatures. In these models, hysteretic responses after steady state is reached are constant and do not change with number of cycles. Both models are capable in capturing transient and steady creep strains when constant stresses are prescribed. The above models do not include the effect of energy dissipation due to creep and inelastic deformations during cyclic loadings.

Several studies have discussed the importance of energy dissipation for monotonic loading conditions. Chaboche [3], Chaboche [4] compared the stored energy and total plastic work for both uniaxial tension and cyclic loading cases. The results show that for a uniaxial tension, the general thermodynamic framework gives a good simulation of the stored energy and plastic work. Chaboche also pointed out that for cyclic loading, the stored energy is released for each half cycle, and thus cyclic loading can accumulate higher energy dissipation. Rosakis et al. [24] discussed the influence of plastic work on temperatures. They also pointed out that for high-strain rate and short loading period, heat loss through conduction, convection or radiation in materials is negligible, hence the process can be assumed to be adiabatic and homogeneous. Predicting fatigue life in materials by incorporating the energy dissipation effect has been considered mostly for polymers, e.g., Constable et al. [5], Sauer and Richardson [25], Janssen et al. [16], Ramkumar and Gnanamoorthy [23], etc. Crawford and Benham [7] indicated that since in contrast to metal, polymers have lower thermal conductivity and higher damping properties, it is more likely for polymers to experience thermal softening failure without crack propagation. To the best of our knowledge, only a few research discussed the relationship between energy dissipation and fatigue lifetime for metals. Halford [14] studied the relation between energy dissipation and material failure under cyclic loading. He investigated 190 sets of fatigue data for both ferrous metals and nonferrous metals. The data are reported in terms of amount of energy being dissipated, stress range, plastic strain range, and number of cycle to failure. He concluded that the total energy being dissipated, referred by fatigue toughness, increases with increasing fatigue life (cycles to failure). Halford [14] also used an empirical model to capture the fatigue failure responses of these metals. Lin and Haicheng [19] related the cyclic fatigue lifetime of two metal Zirconium and Zircaloy-4 with the dissipated energy through a power-law relationship, which is an empirical approach. The plastic energy dissipation results in irreversibility and hysteretic behaviors, and causes a formation of fatigue striations and dislocation patterns. Hence, they used the plastic energy dissipation per cycle as fatigue damage variable. They conducted