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A unified plasticity methodology for rate- and temperature-sensitive alloys exhibiting a non-linear kinematic hardening behavior

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ABSTRACT

In this paper, a novel unified plasticity methodology is proposed to allow the coupling of rate- and temperature-sensitivity of engineering alloys as well as the non-linear kinematic hardening behavior often observed during cyclic loading. The proposed methodology is general in the sense that an arbitrary constitutive model may be chosen for the viscoplastic part, as well as the cyclic part. We adapt our model with a physically-motivated viscoplasticity flow rule and a nonlinear kinematic hardening model. In contrast with other unified plasticity models, the simplified theory involves few material parameters that can be readily calibrated from standard mechanical tests. The capabilities of the proposed theory are demonstrated for a hot rolled annealed 304L stainless steel supplied by Vimetal Peckover. The model is tested with stress–strain curves obtained from standard tensile and cyclic uniaxial tests at various strain amplitudes and strain-rates, and good accuracy of the response is obtained for strains up to 15%, within a temperature range of 293–673 K. We note that the cyclic plasticity model in our adapted theory can be readily enhanced with ratchetting, mean stress relaxation, strain amplitude history, Masing effects or other complex capabilities.

1. Introduction

Stainless steels are ubiquitous in today's cutting-edge fabrication processes and structural design. For instance, austenitic stainless steels of the 300 series retain their high strength and ductility over a wide temperature range as well as provide an excellent resistance to corrosion and oxidation. These interesting properties make them favorable candidates for high performance applications such as aeronautic, nuclear fusion and fission facilities, and many more [1].

The behavior of stainless steels has been studied for almost a century and extensive experimental results can be found in the literature. In the early work of [2], the rate-dependent response of a 304 stainless steel[1] was highlighted through room-temperature tensile tests at different strain-

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[1] Annealed at 1093 °C for 90 min.

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rates. Krempl [2] found that, even at room-temperature, the response of the alloy could vary by up to 25% for strain-rates ranging from 10^{-8} to 10^{-3} s^{-1}. He also observed through cyclic loading at a strain amplitude of $\pm$ 0.2% that the well-known Bauschinger's effect played an important role upon load reversal. These observations were since confirmed numerous times for various stainless steels such as in [1,3–5].

In light of these observations, constitutive modeling of stainless steels, or of any engineering alloy exhibiting both (i) a rate- and temperature-sensitivity and (ii) a non-linear kinematic hardening, requires the development of a predictive theoretical model encompassing these two distinct behaviors simultaneously. Such an approach combining these behaviors is often referred to as a "unified plasticity theory" introduced, among others, by Slavic and Sehitoglu [6], Chaboche and Nouailhas [7] and the references therein. Many variants of unified plasticity theories exist in the literature.

For instance, in [8], plastic flow was described through a piecewise-defined flow rule whose intervals were determined through an effective stress-based criterion. In their theory, the determination of the intervals where the piecewise function apply is done by adjusting the criterion based on experiments, which is not straightforward and requires extrapolation of the experimental data. A similar approach was proposed by Abdel-Karim and Ohno [9], where the flow rule was instead given as a sum of effective stress-dependent subfunctions. These subfunctions are taken as "hypersphere surfaces" whose radii are governed by kinematic variables similar to those used in the classical cyclic hardening theory of Armstrong and Fredrick [10]. However, the large quantity of material parameters involved in their model limits its scope of application. In [11], viscoplasticity was coupled with a yield-type step function used to model cyclic hardening. A limitation of this model comes from this step function which limits the region where viscoplastic flow and non-linear kinematic hardening act simultaneously and therefore the rate- and temperature-sensitive behavior. Similar limitations arise from the work of Ohno and Wang [12,13] where bilinear change of the backstress was used. Therefore, a well-defined methodology for combining aspects of the rate- and temperature-sensitive behavior as well as cyclic kinematic hardening is required. Thereafter, an adapted theory for each plasticity mechanism can readily be chosen from a wide array of existing models such as in [14,15] (thermo-mechanical coupling), and [16–19] (cyclic plasticity).

The purpose of this paper is to present a well-defined unified-type plasticity methodology which combines aspects of the rate- and temperature-sensitive behavior as well as cyclic behavior. Thermodynamic considerations allow the coupled action of both plastic mechanisms simultaneously. We then choose simple constitutive equations: (i) the cyclic, kinematic hardening contribution is modeled using classical notions of backstress and effective stress and (ii) rate- and temperature-sensitive behavior is modeled using a physically-motivated viscoplasticity flow rule. Our simplified theory leads to a constitutive model requiring few material parameters that can be readily calibrated from standard tensile tests; a straightforward numerical plus experimental-based methodology is also proposed for determining the material parameters involved in the model. As an example, the experimental data for hot rolled annealed 304L austenitic stainless steel from [4] and [5] are used to calibrate and test the specialized theory. We point out that the objective of this paper is not to determine the best constitutive model for each plastic mechanism, but to lay out a methodology from which one can choose the one that suits best. Our choice of a simple nonlinear kinematic hardening model, although simple in its calibration and useful in specific loading conditions, is limited when describing complex phenomena such as ratchetting, mean stress relaxation or Masing's effects, where models such as [18,20,21] or [16] should be used.

The paper is structured as follows. The proposed unified plasticity methodology is presented in Section 2. The adapted theory is then applied to an austenitic stainless steel 304L, previously characterized by Paquet and co-workers [4,5]. In Section 3.1, the model is first calibrated from uniaxial tensile tests data obtained at various temperatures but fixed strain-rate. Then, we investigate the room temperature rate-dependent behavior with four different strain-rates so as to calibrate the remaining material parameters. The model is then tested in Section 3.2 with cyclic stress–strain data with different strain amplitudes and strain-rates. Finally, a conclusion is given in Section 4.

2. Unified plasticity constitutive methodology

The unified plasticity methodology proposed for combining the constitutive behavior of metals exhibiting rate- and temperature-sensitivity as well as cyclic hardening is developed in this section. This constitutive model involves the following main governing variables: (i) the Cauchy stress $\mathbf{T}$, (ii) the backstress $\mathbf{T}_{\text{back}}$, arising from the material's non-linear kinematic hardening behavior, and (iii) the absolute temperature ϑ. For simplicity, isothermal conditions are assumed. However, the proposed constitutive equations can be readily extended to the non-isothermal case.

2.1. Strain additive decomposition

The deformation of metals is assumed to be decomposable as (i) an "elastic" deformation due to stretching and rotation of the underlying microstructure and (ii) a "plastic" deformation which, at low homologous temperatures, represents the rate- and temperature-sensitive response of the material as well as the experimentally-observed non-linear kinematic hardening (often referred to as Bauschinger's effect). In other words, this small deformation theory is based on the kinematic decomposition of the infinitesimal strain tensor $\mathbf{E}$ into the elastic $\mathbf{E}^e$ and plastic $\mathbf{E}^p$ parts:

$$\mathbf{E} = \mathbf{E}^e + \mathbf{E}^p, \tag{1}$$

where

$$\mathbf{E} = \frac{1}{2}\left[\left(\frac{\partial \mathbf{u}}{\partial \mathbf{x}}\right) + \left(\frac{\partial \mathbf{u}}{\partial \mathbf{x}}\right)^{\mathrm{T}}\right]. \tag{2}$$