THERMODYNAMIC CONSISTENT FORMULATIONS OF VISCOPLASTICITY AND DAMAGE IN FERRITE STEEL

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Summary A general consistent thermodynamic framework for thermo-viscoplastic and damage deformations of ferrite steel is presented in this study. Microstructural physically based yield function is utilized in this work for dynamic and static deformations of high strength steel. A new energy-based isotropic damage model capable of capturing the evolution of damage throughout the deformation process is also introduced into the constitutive model to describe the degradation of the ferrite alloys. The role of material dependence in setting the character of the governing equations is illustrated in the context of a simple uniaxial compression problem. Results obtained for HSLA-65 and DH-36 steel show good comparisons with experimental results.

INTRODUCTION

High quality steels are used as a skeleton supporting many infrastructure constructions like, for example, skyscrapers, arenas, stadiums, bridges and others. In addition to their use in the construction of bridges, pressure vessels, storage tanks, etc. high-strength, low alloy steel such as HSLA-65 and conventional high strength steel (HSS) such as DH-36 have recently gained increased acceptance in automobile manufacturing and shipbuilding, as these steels provide improved formability and weldability. The understanding of the mechanical behavior of these materials over a wide range of temperatures and strain rates has been the subject of extensive studies in the past few decades, both experimentally and theoretically [1-4]. Studying dynamic localizations particularly the development of shear bands is very important because they dominate the deformation and fracture modes in ferrite steel. Thermodynamics with internal variables offers a solid framework to introduce constitutive equations.

THERMODYNAMIC FORMULATIONS

A thermodynamically consistent mathematical formulation within the context of small deformation is presented in this section as a framework to introduce constitutive equations. Thermodynamics with internal state variables offer both guidelines and some constrains for the choice of evolution equations. Thermo-elastic-viscoplastic deformation behavior is defined using two potentials; the thermodynamic potential to describe the present state and the dissipative potential to describe the irreversible evolution behavior. The formal potential is described through the Helmoltz free energy, ψ , as:

$$\psi = e - sT \quad \rightarrow \qquad \dot{\psi} = (\partial\psi / \partial\varepsilon_{ij}^{e})\dot{\varepsilon}_{ij}^{e} + (\partial\psi / \partial T)\dot{T} + (\partial\psi / \partial p)\,\dot{p} \tag{1}$$

where s is the specific entropy, e is the internal energy and T is the absolute temperature. The choice of evolution equations in a form that does not allow any reversible changes is important. Reversible changes produce instantaneous changes of the internal variables and result in incompatibility with thermodynamics. The determination of these internal state variables is achieved through the use of the fundamental laws of thermodynamics; the conservation of mass, balancing laws, linear and angular momenta, the conservation of energy, and the second law of thermodynamics which reduces to the Clausius-Duhem inequality from which the dissipated potential, Π, is extracted as follows:

$$\left(\sigma_{ij} - \rho\partial\psi / \partial\varepsilon_{ij}^{e}\right)\dot{\varepsilon}_{ij}^{e} - \rho\left(s + \partial\psi / \partial T\right)\dot{T} + \sigma_{ij}\dot{\varepsilon}_{ij}^{vp} - \rho\partial\psi / \partial p - q_i T_{,i} / T \geq 0 \quad \rightarrow \quad \Pi = \sigma_{ij}\dot{\varepsilon}_{ij}^{vp} - R\dot{p} - q_i T_{,i} / T \geq 0 \tag{2}$$

where ρ denotes the mass density, q is the heat flux vector, and $R = \rho\partial\psi / \partial p$ represents the thermodynamic conjugate force associated with the flux of the viscoplastic internal state variable p. In the case of dissipative processes, the viscoplastic dissipation potential is expressed as a continuous and convex scalar valued function of the flux variables, and using the Legender-Frenchel transformation of the viscoplastic dissipation potential, we can obtain complementary laws in the form of the evolution laws of flux variables in terms of the dual variables. Since use is not made of non-linear rules for viscoplastic kinematic hardening in this work, accordingly, the viscoplastic potential F is taken to be the same as the dynamic yield surface of ferrite steel as follows:

$$F = f = \sigma_{eq} - \sigma_{ferrite} = \sigma_{eq} - c_1 - c_2\sqrt{1 - \mathrm{e}^{-c_3 p}} - c_4\left(1 - (c_5 T - c_6 T \ln \dot{p})^{1/q_1}\right)^{1/q_2} \tag{3}$$

The material parameters c_1-c_6 appeared in the above constitutive relations are related to the microstructure physical quantities (see, for more details, Ref. [4]).

In order to simulate damage evolution behavior of ferrite steel, there is a need for introduction of a damage parameter in the above proposed constitutive model. According to the strain equivalence principle, the effective damage coupled yield function for an isotropic damage parameter φ can be written as follows:

$$\sigma_{eq} = \left(3\left(\tau_{ij} / (1-\varphi)\right)\left(\tau_{ij} / (1-\varphi)\right) / 2\right)^{1/2} \tag{4}$$

Consequently, the evolution expressions of the internal variables yield

$$\dot{\varepsilon}_{ij}^{vp} = \dot{\lambda}^{vp}(\partial F / \partial\sigma_{ij}) / (1-\varphi) = \dot{\lambda}^{vp}3(\tau_{ij}) / 2(1-\varphi)\sigma_{eq} = \dot{\lambda}^{vp}N_{ij} / (1-\varphi); \qquad \dot{p} = \dot{\lambda}^{vp} \tag{5}$$

Damage evolution definition

The structural behavior of steel, as many structural materials, changes during deformation processes under complex mechanical loadings. The damage process may start at some point in the deformation process in the form of micro-cracks and micro-voids leading at its latest stage to the development of macro-cracks and consequently material failure. The proposed model treats damage, φ, as an increase in the dissipated energy of the material and consequently a reduction in its ability to absorb further energy prior to failure. It defines damage at a certain level as the ratio between the dissipated energy at that level and the dissipated energy at failure as given below [5]:

$$\varphi = \left(\Pi / \Pi_{\mathrm{T}}\right)^{\alpha} \varphi_{\mathrm{f}}\left(\dot{\mathrm{p}}, \mathrm{T}\right) \tag{6}$$

where φ_f is the critical damage at failure and Π_T is the corresponding total dissipated energy. The exponent α is a constant that determines the trend of damage evolution throughout the deformation process. The model assumes that the elastic deformations are very small relative to the plastic deformations and thus, damage initiates and propagate with the initiation and accumulation of viscoplastic deformation.

RESULTS AND CONCLUSIONS

A 3D formulation model was developed based on the additive decomposition of the rate of deformation and use was made of the incremental integration scheme in which the stress objectivity was preserved for finite rotation increments to rewrite the constitutive relations in a corotational moving frame. Finite element simulations were performed by implementing the proposed coupled damage-viscoplasticity constitutive model, using an implicit stress integration algorithm based on the radial return and the backward-Euler integration algorithms. This was conducted within the commercial finite element program ABAQUS/Explicit via a user's material subroutine coded as VUMAT. An axisymmetric uniaxial compression problem subjected to low and high velocities and initial temperatures was considered as shown in Fig. 1. This example was conducted in order to demonstrate the capability of the FE formulation to capture the stress-strain curves as compared with the experimental results for two types of ferrite steels; DH-36 and HSLA-65. Due to symmetry, only a quarter of the cylindrical specimen is considered and solved using a mesh of one axisymmetric element (CAX4R ABAQUS type) with the boundary conditions defined in Fig. 1. The available experimental data for the two considered alloys were obtained at a wide range of initial temperatures (77K-700K) and strain rates (0.001-8500s^{-1}). For this, two low velocities of 10μm/s, 1.0mm/s and two high velocities of 30m/s and 85m/s that is equivalent, for the present problem dimensions, to strain rates of 0.001s^{-1}, 0.1s^{-1}, 3000s^{-1}, and 8500s^{-1}, respectively, were considered to study the effect of the initial temperature on the stress-strain curves. This compression velocity is kept constant during certain time steps that achieve about 50% -60% true straining of the sample in the axial direction. A good comparison between the computed results using VUMAT subroutine and experimental data was observed in all the cases especially when it comes to high strain rates and temperatures (e.g., Fig. 2 and Fig. 3).

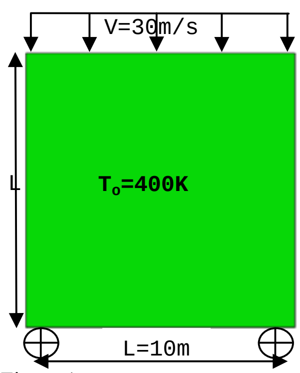

Figure 1 Axisymmetric simple uniaxial compression modeled in ABAQUS, V=30 m/s and T$_o$ = 400K.

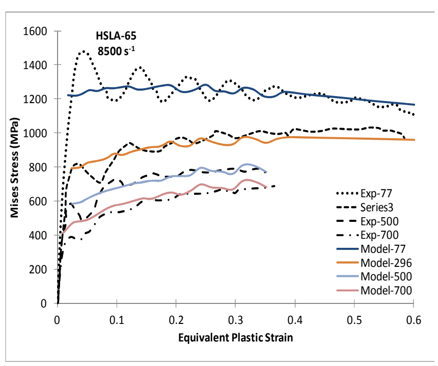

Figure 2 Comparisons of the adiabatic true stress-true strain between experimental and FE results for HSLA-65 at 8500 s^{-1} and different temperatures.

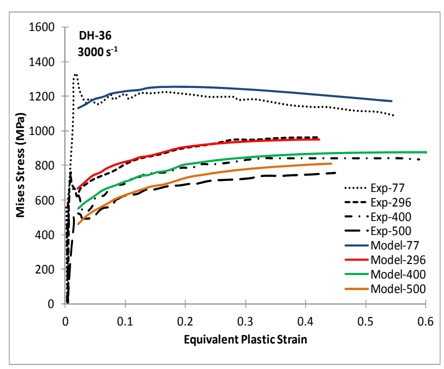

Figure 3 Comparisons of the adiabatic true stress-true strain between experimental and FE results for DH-36 at 3000 s^{-1} and different temperatures.

References

[1] Nemat-Nasser S., Guo W.: Thermomechanical response of DH-36 structural steel over a wide range of temperatures and strain rates. *Mech Mate* 35**:** 1023–1047, 2003.

[2] Nemat-Nasser S., Guo W.: Thermomechanical response of HSLA-65 steel plates: experiments and modelling. *Mech Mate* 37: 379–405, 2005.

[3] Abed, F.H., Voyiadjis, G. Z.: Plastic deformation modeling of AL-6XN stainless steel using a combination of bcc and fcc mechanisms of metals. *Int. J. of Plasticity*, 21: 1618-1639, 2005.

[4] Abed, F.H.: Constitutive modeling of the mechanical behavior of high strength steels for static and dynamic applications. *Mech Time-Dependent Mater* 14: 329-345, 2010.

[5] Abed, F.H., Al-Tamimi, A., Alhamiri, R.: Characterization and modeling of ductile damage in structural steel at low and intermediate strain rates. Submitted for publications in the *ASCE J. Engng Mech*, 2012.