Improvement on the Modeling of Rate-Dependent Plasticity and Cyclic Hardening by Bodner-Partom Model

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Abstract: An additional isotropic internal variable is utilized to extend the Bodner-Partom unified viscoplastic constitutive model (original B-P) to improve the modeling of rate-dependent plasticity and cyclic hardening behaviors of metals. The extended model (new B-P) contains two isotropic internal variables: one plays the role of representing the fast hardening in smaller inelastic strain range, while the other evolutes at slower speed accompanied by larger accumulated inelastic deformation, such as cyclic hardening. To examine the validity of the extended constitutive model, the rate-dependent plasticity of a Ni-base superalloy Udimet 720Li at 650℃ and 700℃ are characterized using both models. Not only numerical simulations are conducted for various loading conditions by implementing both models into ABAQUS using a user material subroutine, also a systematic comparison between two models is completed. Numerical results show that the extended material constants in the new model provide more flexible capability in modeling the inelastic behavior of the material with sound accuracy.

Key words: space propulsion; superalloy; constitutive relation; viscoplasticity; internal state variable

对 **B P** 本构模拟材料率相关塑性变形和循环硬化的改进. 石多奇, 杨晓光, 王延荣. 中国航空学报(英文版), 2005, 18(1): 83-89.

摘 要: 对 Bodner-Partom 统一黏塑性本构理论(B-P 模型)进行了修正, 改善了其对材料加载速率相关的黏塑性和循环硬化的模拟精度。改进模型包含两个各向同性硬化内变量: 一个用于描述小非弹性应变范围内快速的各向同性硬化, 另一个以缓慢的演化速率来表述大的累积非弹性变形, 如循环硬化过程中非弹性应变累积。利用 ABAQUS 的用户材料子程序将改进模型编成有限元计算代码, 通过对镍基合金 Udimet 720Li 率相关黏塑性特征的本构模拟对其进行了验证, 并与 B-P 模型作了对比。结果表明改进模型能够以更高精度、更加灵活地对材料的非弹性力学行为进行建模。

关键词: 航空航天推进系统; 高温合金; 本构关系; 黏塑性; 内变量

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In the past three decades, considerable progress has been made in the area of the so-called "unified" constitutive theories and several new or improved thermo-viscoplastic formulae have been proposed and evaluated in high temperature applications, mainly in components subjected to thermal-mechanical loading conditions. For example, Mroz(1969)[1], Philips and Wu(1973)[2], Bodner and Partom (1975)[3], Kriege(1975)[4], Dafalias (1980)[5], Drucker and Palgen(1981)[6], Eisenberg and Yen (1981)[7], Walker (1981)[8], Chaboche(1989)[9], Yoshida(2000)[10], Voyiadjis and Zolochevsky(2000)[11], Rosakisa, *et al* (2000)[12], Järvstråt(2002)[13], established different constitutive equations based on thermodynamics and dislocation dynamics. The kernel of the viscoplastic equations is that all observed effects, such as rate-dependent plasticity, cyclic hardening (softening), creep and stress relaxation, are a result of the same internal physical processes[14]. That is, single or multiple internal variables could be used to represent time-dependent creep and time-independent plasticity. The evolutionary equations of the internal state variables are based on

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their microstructure evolution, which are regarded as being a better approach of the governing physical processes than the classical plastic and creep theories for those complex loading conditions. Therefore, the unified method is expected to have superior capabilities for prediction of nonlinear responses of material, especially at elevated temperature.

Bodner-Partom model uses plastic work to describe the materials resistance to plastic flow rather than inelastic strain, without an explicit yield criterion. Since 1970's, the theory was widely used in modeling the constitutive characteristics of various coppers and superalloys and was made great progress, especially in NASA HOST program[15-17]. There are many applications using basic Bodner-Partom theory in constitutive modeling of various engineering materials, such as RMI-40[3], annealed OFHC copper[18,19], Ni-based superalloy B1900 + Hf[17], Hastelloy-X and aluminum alloy 8009[20], INCONEL 690[21], OFE copper and 70/30 α brass[22]. Most of these works were mainly focused on the work-hardening characteristic of B-P model for monotonic loading. Few paid attention to the mechanical responses for cyclic loading and creep loading.

Generally, the deformation of superalloy used in turbomachine is very small, viz. < 1.0%, and it is difficult to distinguish elastic and plastic components. Hence, from the viewpoint of life prediction of turbine components, the stress-strain behaviors under cyclic and tensile deformation condition has to be described precisely by advanced constitutive equation, because the subsequent creep deformation of the components is evaluated based on the calculated state of both stress and strain. However, numerical simulation of the mechanical behavior of a γ' strengthened Ni-base polycrystalline superalloy Udimet720Li revealed that in the original Bodner-Partom unified constitutive theory, only one isotropic hardening variable was limited in describing the different mechanisms of hardening under monotonic loading and cyclic loading[23,24]. Therefore, an objective of the present study is to consider improving possibilities that are offered by some modification to the original Bodner-Partom theory that can accurately characterize the mechanical behaviors. A systematic comparison of the model and their properties are made in the viscoplastic framework and for the monotonic tension and tension-compression cases. It is found that the extended material constants in more than one isotropic hardening rule provides more flexible capability in modeling the inelastic behavior of the material with sound accuracy.

1 Numerical Simulation by B-P Model

The Bodner-Partom theory is consisted of viscoplastic flow rule and the evolutionary equations of internal state variables. An explicit yield criterion is not required. The basic constitutive equations are as following[15,20,23]

$$\dot{\varepsilon}_{ij} = \dot{\varepsilon}_{ij,\mathrm{e}} + \dot{\varepsilon}_{ij,\mathrm{in}} \tag{1}$$

$$\dot{\varepsilon}_{ij,\mathrm{in}} = D_0 \exp\left[-\frac{1}{2}\left(\frac{(Z_\mathrm{I}+Z_\mathrm{D})^2}{3J_2}\right)^n\right]\frac{S_{ij}}{J_2} \tag{2}$$

$$\dot{Z}_\mathrm{I} = m_1\left[Z_1 - Z_\mathrm{I}(t)\right]\dot{W}_\mathrm{p}(t) - A_1 Z_1\left[\frac{Z_\mathrm{I}(t)-Z_2}{Z_1}\right]^{r_1} \tag{3}$$

$$Z_\mathrm{D}(t) = \beta_{ij}(t)\,\boldsymbol{u}_{ij}(t) \tag{4}$$

$$\dot{\beta}_{ij}(t) = m_2\left[Z_3\boldsymbol{u}_{ij}(t) - \beta_{ij}(t)\right]\dot{W}_\mathrm{p} - A_2 Z_1\left[\frac{(\beta_{kl}\beta_{kl})^{1/2}}{Z_1}\right]^{r_2}\boldsymbol{v}_{ij} \tag{5}$$

$$\boldsymbol{u}_{ij}(t) = \frac{\sigma_{ij}(t)}{(\sigma_{kl}\sigma_{kl})^{1/2}};\ \boldsymbol{v}_{ij}(t) = \frac{\beta_{ij}(t)}{(\beta_{kl}\beta_{kl})^{1/2}} \tag{6}$$

Here, $\dot{W}_\mathrm{p} = \sigma_{ij}\dot{\varepsilon}_{ij,\mathrm{in}}$ is the inelastic work. The initial condition is $Z_\mathrm{I}(0) = Z_0$ and $\beta_{ij}(0) = \mathbf{0}$. Physical meaning of material constants D_0, Z_0, Z_1, Z_2, Z_3, m_1, m_2, n, A_1, A_2, r_1 and r_2, were discussed and could be obtained through an optimum program in Ref. [23]. For simplicity, these basic set of material parameters is reffered to as "old" B-P constants. The simulated results for Udimet 720Li are shown in Fig. 1 and Fig. 2.

It is observed that acutely transient nonlinear change occurs at the knee of the stress-strain curves, and the original B-P model overpredicts the hardening stress range for some initial cycles, but gradually approaches to complete shakedown of cyclic hardening, which is in contrast to the exper-