A MODEL OF CYCLIC VISCOPLASTICITY WITH SPECIAL REFERENCE TO YIELD-POINT PHENOMENA

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Summary A model of viscoplasticity that describes the yield-point phenomena is presented. This paper describes its modeling and some strong features of this model by comparing the numerical simulations and the corresponding experimental data on fundamental cyclic plasticity, such as rate-dependent cyclic straining and ratcheting. Furthermore, as an example of industrial application of this model, a result of finite element numerical simulation on skin-pass rolling of a sheet metals is presented.

INTRODUCTION

Annealed steels and some bcc metals, as well as some aluminum alloys, exhibit a sharp yield point and the subsequent abrupt yield drop followed by the yield plateau in the stress-strain curves of uniaxial tension. The yield-point phenomena are strongly rate dependent, e.g., the flow stress levels, especially the upper and lower yield strengths, increase with increasing strain rate, and furthermore, the Luders strain becomes larger with the rate. As for cyclic plasticity behavior, the Bauschinger effect is clearly observed even in a cyclic straining at yield plateau region. Constitutive modeling of such rate-dependent yield-point phenomena, as well as the subsequent cyclic plasticity, is of vital importance, since in most of cases of small-scale yielding, plastic deformation occurs in the Luders strain range, but not in the workhardening region. Nevertheless, most of discussions of constitutive modeling so far published scarcely touched this problem.

The present author [1] has recently proposed a constitutive model of cyclic plasticity which takes into account the yield-point phenomena. The first part of this paper presents an extended version of this model, which properly describes the above-mentioned rate-dependent yield-point phenomena and the subsequent cyclic plasticity behavior. The second part of this paper demonstrates how it works in the numerical simulation of cyclic plasticity, such as cyclic straining and ratcheting. Moreover, as an industrial application of this model, a result of FE simulation of skin-pass rolling, which is a process for erasing the yield-point and non-uniformly plastic deformation of sheet metals, is presented.

CONSTITUTIVE MODELING

The framework of viscoplastic constitutive model is constructed based on the overstress theory on the premise that the sharp yield point and the subsequent abrupt yield drop result from rapid dislocation multiplication and the stress dependence of dislocation velocity [2], which is given by the following equations:

$$\dot{\bar{\varepsilon}} = \frac{b\rho_m}{M}\left\langle \frac{\bar{\sigma}-Y}{D} \right\rangle^n, \quad \dot{\boldsymbol{\varepsilon}}^p = \frac{3(\boldsymbol{s}-\boldsymbol{\alpha})}{2\bar{\sigma}}\dot{\bar{\varepsilon}}, \quad \bar{\sigma} = \sqrt{\frac{3}{2}(\boldsymbol{s}-\boldsymbol{\alpha}):(\boldsymbol{s}-\boldsymbol{\alpha})}$$

where $\dot{\boldsymbol{\varepsilon}}^p$ and $\dot{\bar{\varepsilon}}$ are the plastic strain rate and its effective value, and $\boldsymbol{s}$ and $\boldsymbol{\alpha}$ are the stress and back stress deviators, and Y: the radius of yield surface; D: drag stress; b: the Burgers vector; ρ_m: mobile dislocation density; M: Taylor factor. The yield surface kinematically moves within the bounding surface which has isotropic/kinematic hardenings [3]. In addition, workhardening stagnation for the bounding surface, of which rule has been proposed by the present authors [3], is assumed. To describe the rapid multiplication of mobile dislocation density, ρ_m, the rule of evolution equation of the fraction of mobile dislocation density [1] is employed. Furthermore, in the present paper, a new rule to distinguish two regimes, i.e., yield-drop and workhardening regimes, is introduced.

Figure 1 shows an example of stress-strain responses of a material element in uniaxial tension predicted by the present model. It clearly shows the rate dependent stress-strain responses, which consist of two parts: one is yield-drop regime characterized by the sharp yield-point and the subsequent yield drop (softening), and the other workhardening region. It should be noted that this is a stress-strain response for a material element, but not for a stress vs. gage-length strain curve observed in uniaxial tension experiment where non-uniformly plastic deformation occurs in a specimen. If this model is used for FE simulation of uniaxial tension experiment for a real shape of specimen, the calculated result will show almost flat yield plateau as a result of the simulation of the Luders band propagation.

NUMERICAL SIMULATIONS OF VARIOUS ASPECTS OF YIELD-POINT PHENOMENA

Uniaxial Tension and Cyclic Plasticity Deformations

This model has a capability of reproducing realistic stress-strain curves in uniaxial tension, where the rate dependence of flow stress in the yield plateau is much stronger than in workhardening region, and the Luders strain becomes larger with increasing strain rate. This model can also well simulate cyclic plasticity deformations. Figure 2 shows an example of FE numerical simulation of stress-stress response in ratcheting, where the rate of strain accumulation is fast at an early stage of ratcheting and it tends to shakedown, which are consistent with the experimental observations [1]. Deformation characteristics of cyclic straining and strain-controlled ratcheting are also studied in the present work.

In a specific case of uniaxial tension, extremely high upper yield point, as high as almost twice of the lower yield strength, is found in a center-annealed specimen of a mild steel wire (see its FE simulation in Fig. 3a). However, such a high yield point disappears in a uniformly annealed specimen (see Fig. 3b), because the Luders band propagates from a vicinity of the specimen clamp where plastic deformation zone had been formed by clamping. These phenomena are discussed based on FE simulation.

Modeling of Strain Aging

Strain aging behavior, characterized by the reappearance of the upper yield-point and the increase of flow stress due to aging, is simulated by this model. In the modeling of aging, mobile dislocation density is assumed to be initialized due to dislocation locking, and the isotropic hardening of the bounding surface, caused by the precipitate hardening, is introduced.

FE simulation of Skin-Pass Rolling

Skin-pass rolling, where sheet-thickness reduction is as small as 1-2%, is a popular process conducted at the final stage of sheet metal rolling for the purpose of erasing yield point and non-uniform deformation of sheet metals. To understand the mechanism of erasing of yield point, FE simulation of skin-pass rolling was performed. From the simulation it was found that, after skin-pass rolling, plastic strain covers all over the sheet, therefore, in the subsequent uniaxial tension the upper yield point no longer appears.

CONCLUDING REMARKS

The present model of cyclic viscoplasticity well describes several aspects of rate-dependent yield-point phenomena, and it is a powerful tool for understanding the mechanism of yield-point phenomena, and also for numerical simulations of many industrial applications such as structural analyses and metal forming simulations.

References

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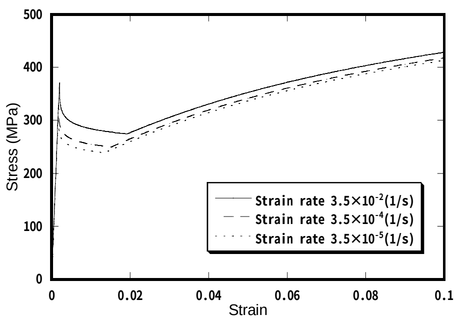


Fig.1 Stress-strain response in uniaxial tension of a material element calculated by the present model.

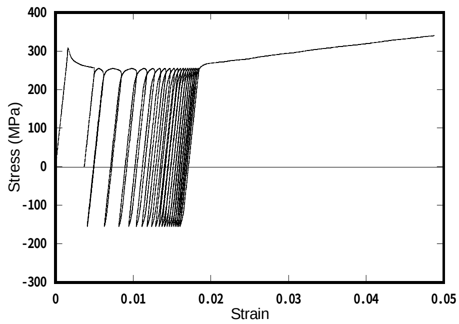
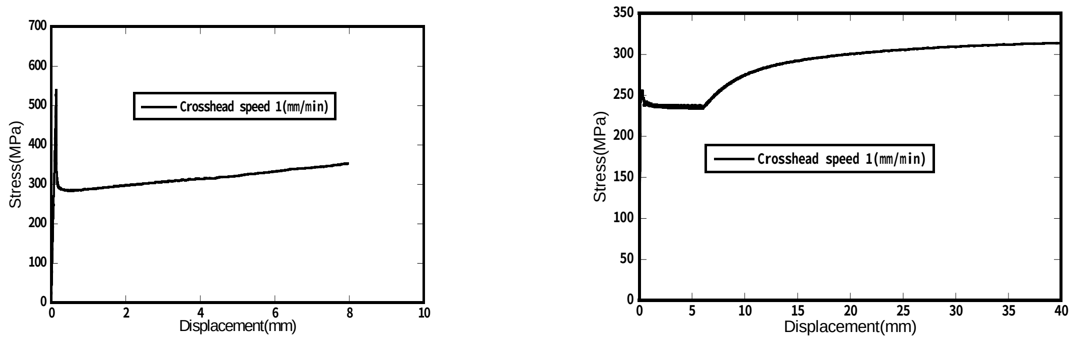


Fig.2 Numerical simulation of ratcheting of a mild steel.



a) b)

Fig. 3 Calculated results of stress-displacement curves for a) a center-annealed specimen and b) a uniformly annealed specimen of a mild steel wire.