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Prediction of mechanical behavior of ferrite-pearlite steel

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ABSTRACT

A new approach describing the flow stress of ferrite-pearlite steel has been proposed, which divided the deformation process into three stages based on whether ferrite or pearlite yielded. Iso-work increment assumption was applied to describe the transfer of load between the components. The physically based model to describe ferrite was approximated with Swift's equation in order to obtain the analytic solution. The tensile strength of ferrite-pearlite had a linear relation with pearlite volume fraction, square root reciprocal of ferrite grain size and reciprocal of pearlite interlamellar spacing. Moreover, a model to calculate the tensile strength of ferrite-pearlite steel was proposed. The predicted values of tensile strength were in good agreement with experimental results when the pearlite volume fraction was less than 20%. Considering the plastic relaxation mechanisms, the internal stress was modified with pearlite volume fraction, total strain, yield stress of ferrite and pearlite when the pearlite volume fraction was more than 20%.

1. Introduction

Ferrite-pearlite steels are widely used and have been studied for many years. Ferrite-pearlite microstructures are the intermediary state of hot-rolled strips for production of high strength steels. Furthermore, the majority of the hot strip steels are directly delivered to customers. Modeling the mechanical properties of such microstructures is important for industry.

Ferrite-pearlite microstructure can be considered from the point of the interactions between two ductile phases. Several kinds of deformation theories on the two ductile phases alloys have been proposed including dislocation density theory, self-consistent continuum model, numerical simulations like multiscale modeling and mixture law based model[1-8].

In dislocation density theory, the geometrically necessary dislocations were produced for the compatibility condition at the grain boundary or at the interface in a polycrystal. The theory could well explain the work-hardening rate at a strain near the starting of necking on tensile test where little change in the average internal stress seemed to occur, but had a large discrepancy at small strain[9,10].

In the self-consistent continuum model, all dislocations moving in the soft phase were assumed to pile up against the interface and to produce the long range internal stress. The model neglected plastic relaxation which could reduce internal stress[11,12].

Multi-scale analyses have been recently achieved by Lindfeldt and Ekh[13] and Watanabe et al.[1] in order to predict the mechanical behavior of ferrite-pearlite steels. They introduced three scales (the nano-scale of cementite and ferrite bi-lamellas, the micro-scale of grains interaction and the macro-scale) and used the concept of computational homogenisation. Laschet et al.[14] took the incipient behavior of cementite into account for the prediction of the effective pearlite behavior and its subsequent impact on the effective anisotropic elasto-plastic behavior of the pearlite-ferrite pipeline steel at the macro-scale. Berisha et al.[15] focused on representative volume elements (RVE)-based strategy for modeling the hardening and failure behavior of a ferrite-pearlite steel at different length scales (meso-scale and micro-scale) instead of finite element method. Although numerical simulations could clarify stress and strain distribution in two-ductile-phases alloy, they strongly depended on the boundary conditions and the unit cell describing morphology of pearlite[16,17], resulting in poor applications in engineering.

Mixture law based model has been widely used, in which flow stress of ferrite and pearlite were de-

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scribed with the Holloman's power law equation or the Swift's equation, and a fitting parameter was needed in order to indicate the absolute amount of the stress and strain transfer[7,18-20]. Bouaziz and Buessler[21] proposed a new assumption (Iso-work increment assumption) which could avoid the need for an optional fitting parameter. As only numerical solution could be obtained, it was not a proper method for engineering.

All of the methods mentioned above have limited ranges of application in engineering from the point of view of convenience and accuracy. In this study, a new approach describing the flow stress of ferrite-pearlite steel has been proposed. The approach divided the deformation process into three stages based on whether ferrite or pearlite yielded. The physically based model to describe ferrite was approximated with the Swift's equation in order to obtain the analytical solution. The stress and strain transfer between ferrite and pearlite were described based on iso-work increment assumption. The relationships between tensile strength and pearlite volume fraction, ferrite grain size and pearlite interlamellar spacing were explored and a model to calculate the tensile strength of ferrite-pearlite steel was proposed. The internal stress in ferrite-pearlite steel was modified in order to improve the prediction accuracy.

2. Model for Tensile Behavior of Ferrite-pearlite Steels

A number of studies about dual phase alloys have considered the plastic properties of the alloys in terms of the state of deformation or flow properties of the constituent phases. A general form of the law of mixtures was suggested by Tamura, Tomota, and Ozawa[22]:

$$\sigma(\varepsilon)=(1-F)\cdot\sigma_1(\varepsilon_1)+F\cdot\sigma_2(\varepsilon_2) \tag{1}$$

$$\varepsilon=(1-F)\cdot\varepsilon_1+F\cdot\varepsilon_2 \tag{2}$$

where, σ and ε are the stress and strain of steel, respectively; σ_1 and ε_1 are the average stress and strain in the first phase; σ_2 and ε_2 are the average stress and strain in the second one; and F is the volume fraction of the second phase.

Different localization laws have been used to describe the transfer of load and deformation between the components. In this paper, an asumption called IsoW (iso-work increment) has been considered[19,21]. The concept supposes that mechanical work increment is taken equal in each phase and the equality is expressed as follows:

$$\sigma_1\cdot d\varepsilon_1=\sigma_2\cdot d\varepsilon_2 \tag{3}$$

Combining Eqs. (1)－(3), the flow stress during the deformation of dual phase alloys can be obtained. The tensile properties can also be deduced by applying the necking onset criterion (Considere's criterion)[23]:

$$\sigma-d\sigma/d\varepsilon=0 \tag{4}$$

There are three stages in the deformation of ferrite-pearlite steel, which is schematically explained in Fig. 1. In stage 1, both ferrite and pearlite are elastic; in stage 2, only ferrite deforms plastically while pearlite remains elastic; in stage 3, both ferrite and pearlite deform plastically.

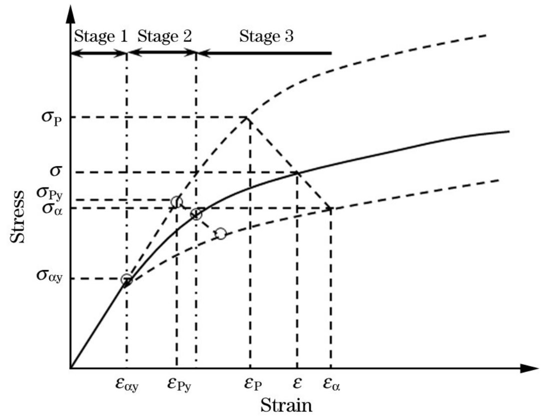

Fig. 1. Schematic illustration of three stages in ferrite-pearlite steel deformation.

In elastic deformation stage (stage 1), ferrite and pearlite obey the Hook elastic law:

$$\sigma_{\alpha e}=E_{\alpha e}\varepsilon_{\alpha e} \tag{5}$$

$$\sigma_{Pe}=E_{Pe}\varepsilon_{Pe} \tag{6}$$

where, $\sigma_{\alpha e}$ and σ_{Pe} are the stress for ferrite and pearlite, respectively; $\varepsilon_{\alpha e}$ and ε_{Pe} are the strain for ferrite and pearlite, respectively; $E_{\alpha e}$ and E_{Pe} are the Young's modulus for ferrite and pearlite respectively, both of which are equal to 210 GPa.

Ferrite and pearlite have the same strain in this stage by combining Eqs. (3), (5) and (6). It transforms to stage 2 when ferrite yields. The plastic behavior for pure ferritic steel can be written as[24,25]:

$$\sigma_{\alpha p}=\sigma_0+\alpha M\mu\sqrt{b}\sqrt{\frac{1-\exp(-Mf\varepsilon_{\alpha p})}{fL}} \tag{7}$$

where, $\sigma_{\alpha p}$ and $\varepsilon_{\alpha p}$ are the plastic stress and strain of ferrite; α is a constant close to 0.33; M is the average Taylor factor ($M=3$); μ is the shear modulus ($\mu=80$ GPa); b is the Burgers vector ($b=2.5\times10^{-10}$ m); L is the dislocation mean free path and can be replaced by the ferrite grain size d; and f is defined as $\frac{10^{-5}}{d}$.

The strain independent term σ_0 takes the Peierls stress into account and the influence of the alloying elements (in wt. %) can be defined as:

$$\sigma_0=77+80w_{Mn}+750w_P+60w_{Si}+80w_{Cu}+45w_{Ni}+60w_{Cr}+11w_{Mo}+5\,000(C_{ss}+N_{ss}) \tag{8}$$

where C_{ss} and N_{ss} represent the contents of carbon and nitrogen in solid solution, respectively.

It is worth noting that only the numerical solution