MICRO-STRUCTURAL DAMAGE ANALYSIS FOR PREDICTING THE EFFECT OF LOADING PATH ON DUCTILITY OF TWO-PHASE STEELS

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Abstract
The purpose of this study is to predict the effect of loading path on ductility of two-phase steels based on micro-structural damage analyses. A micro-structural damage model that consists of 3D micro-structural FE-model and ductile damage model is proposed. Isotropic / kinematic hardening model is introduced for considering the mechanical behavior of Bauschinger effect. The effective damage concept for considering micro-scopic behavior of Bauschinger effect which is dislocation behavior in loading path change is introduced into the damage model. Two types of ferrite-pearlite two-phase steels with different volume fraction of pearlite, and ferrite and pearlite single-phase steels are used. Tensile tests using micro-tensile specimen extracted orthogonal to pre-strained direction from tensile pre-strained round-bar specimens are conducted. Ductility is increased due to loading path change, and the effect is greater in the case of higher volume fraction of pearlite. The mechanism of the effect is analyzed by numerical simulation based on the proposed micro-structural damage model. It is presented that the improvement of ductility by loading path change is caused by micro-structural heterogeneity, delay of necking due to mechanical behavior of Bauschinger effect, and non-effective plastic strain for damage evolution due to micro-scopic behavior of Bauschinger effect.

1. Introduction
Two-phase steels with micro-structural strength mis-match have been developed to improve balance of strength and ductility. In general, ductility of two-phase steels depends on loading path. However, relationships between the effect of loading path on ductility and micro-structural heterogeneity of two-phase steels have not been clarified. This study quantitatively predicts the effect of loading path on ductility of two-phase steels based on micro-structural damage analyses.

2. Micro-structural damage model
In this study, micro-structural damage model for predicting the effect of loading path on ductility is proposed by modifying damage model to consider Bauschinger effect, which consists of "3D micro-structural model" and "ductile damage model". "3D micro-structural model" is the FE-model that reproduces micro-structural morphology of two-phase steels by using Voronoi tessellation method. The micro-structural morphology with various geometry of crystal grains such as grain size, aspect ratio, volume fraction and distributions of second phase can be created. On the other hand, "ductile damage model" can simulate damage evolution up to micro-voids / micro-cracks formation. A unit cell that nano / sub-micro scale damage can be homogenized is assumed. It is necessary for predicting the effect of loading path that mechanical behavior and micro-scopic behavior of Bauschinger effect should be considered. Isotropic / kinematic combined hardening model is applied for the ductile damage model for considering mechanical behavior of Bauschinger effect as follows.

$$\Phi = \left(\frac{\bar{S}}{\bar{s}}\right)^2 + a_1 D^* \exp\left(a_2 \left|\frac{S_{\mathrm{m}}}{\bar{s}}\right|\right) - 1 = 0 \tag{1}$$

$\bar{S}$ and S_{m} are isotropic component of equivalent stress and hydrostatic stress of the unit cell, respectively, $\bar{s}$ is isotropic component of flow stress of the material matrix, a_1 and a_2 are material parameters that can be identified by smooth / notched round-bar tensile tests, and D^* is effective damage fraction. On the other hand, effective damage concept proposed by one of the authors is introduced into the ductile evolution law for considering micro-scopic behavior of Bauschinger effect. The effective damage concept assumes that material damage evolution is not occurred until equivalent back stress $\bar{A}$ of the unit cell related to dislocation structure in materials reaches 95 % of maximum equivalent back stress $\bar{A}_{\mathrm{max}}$ under previous loading.

$$dD = \begin{cases} 0 & \text{for} \quad \bar{A} \leq x\bar{A}_{\mathrm{max}} \\ (1-D)\,|dE_{\mathrm{m}}^{\mathrm{p}}| & \text{for} \quad \bar{A} > x\bar{A}_{\mathrm{max}} \end{cases} \quad , \quad x = 0.95 \tag{1}$$

dD is an increment of damage fraction and $dE_{\mathrm{m}}^{\mathrm{p}}$ is an increment of plastic component of volumetric strain. Simulation method based on the proposed micro-structural damage model is shown in Fig. 1.

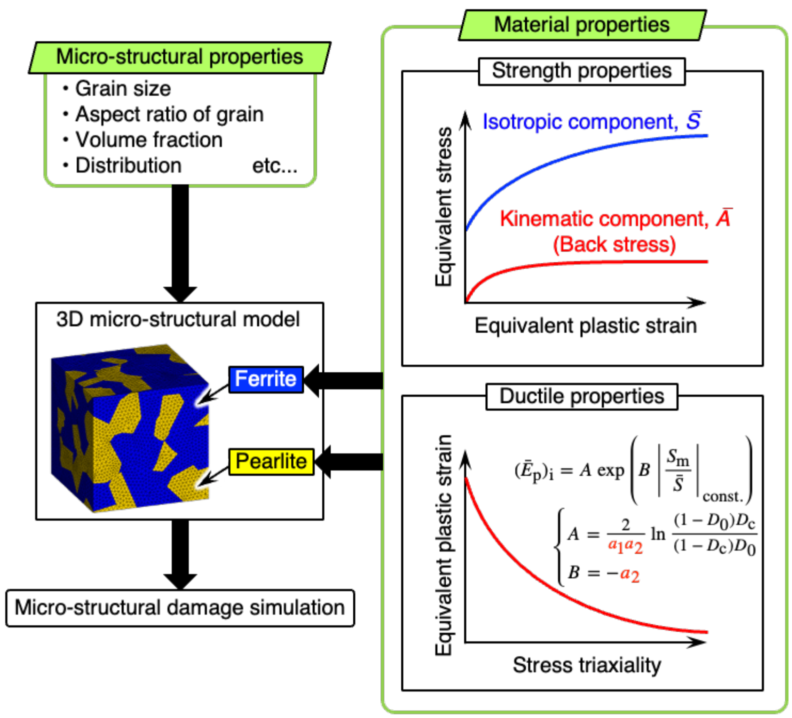

Fig. 1 Numerical simulation method based on the proposed micro-structural damage model.

3. Results

In this study, two types of ferrite-pearlite two-phase steels with different volume fraction of pearlite, and ferrite and pearlite single-phase steels were used. Smooth micro-tensile specimens were extracted from tensile pre-strained smooth round-bar specimen in orthogonal to pre-strained direction. Ductility of the two-phase steel with high volume fraction of pearlite exhibited high dependence on loading path. Numerical simulation based on the micro-structural damage model was conducted for predicting the effect of loading path on ductility. 3D micro-structural model was created from micro-structural properties observed. The material properties of each phase were obtained by round-bar tensile tests for ferrite and pearlite single-phase steels. The predicted stress-strain curve by simulation were in good agreement with experimental results. It was presented by the simulation that the improvement of ductility by loading path change was caused by micro-structural heterogeneity, delay of necking due to mechanical behavior of Bauschinger effect, and non-effective plastic strain for damage evolution due to micro-scopic behavior of Bauschinger effect.