Finite Element Analyses of Elasto-plastic Deformation in Pearlite Lamellar and Colony Structures

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Abstract. Elasto-plastic tensile deformations in pearlite lamellar and two-colony structures are studied by finite element analyses to investigate the effects of lamellar thickness ratio and difference of lamellae orientation of two colonies in pearlite microstructure. The results obtained from plastic strain distributions in lamellar and colony structures show that plastic deformation in cementite lamellar stabilized when ferrite lamellar is thicker than cementite lamellar thickness and plastic strain concentrates when the difference between cementite lamellar orientation in two colonies are larger than 45°.

Introduction

Elasto-plastic deformation in the microstructure of pearlite has been a point of interest in the field of steel research because it exhibits superior balance of strength and ductility. The microstructure is composed of blocks of the same ferrite crystal orientation colonies. The colonies consist of lamellar structure composed of brittle cementite and ductile ferrite lamellae piled up alternately in the same alignment. Strength of pearlite is influenced by interlamellar spacing and its ductility depended on the colony boundaries [1]. However the detailed aspects of those properties coexistence are still ambiguous.

In our previous study [2], we found that the brittle cementite lamella could deform into plastic range if yield stress and strain hardening rate of the ferrite phases are sufficiently large, which we considered to take place from the interlamellar spacing effect. In the analyses, the models were made to be the same thickness although the characteristics of the microstructural parameters should be significantly influenced by the thickness ratio of ferrite to cementite. Therefore, how the lamellar thickness ratio effects to the pearlite ductile deformation is left for further analysis.

Recently, it is experimentally showed that strain tends to concentrates at colony boundary where the cementite lamellae alignment are approximately 45° inclined towards the tensile direction [3]. Thus, to increase the ductile property of pearlite, it is important to establish the presence or absence of the degree which plastic deformation tends to concentrates at colony boundary. In this paper, we study how the lamellar thickness ratio of cementite and ferrite affects the stability of cementite deformation and how the difference between cementite lamellae alignment of adjacent colonies affects the deformation of colony boundaries.

Numerical Models for Lamellar and Colony Structure of Pearlite

We employed a classical theory of the elasto-plastic deformation of metals where the onset of plastic deformation is defined by yield condition of von Mises:

$$\sigma_{eq.} - \sigma_Y = 0 \tag{1}$$

where σ_Y and $\sigma_{eq.}$ denote the yield stress of the material and the equivalent stress, respectively. The ferrite phase hardens after the yield point in the isotropic manner, while the cementite phase is assumed to deform plastically without hardening. We used a commercial software package of ANSYS for finite element analysis, where elasto-plastic deformation is analyzed by the incremental procedure and assuming the associated flow rule.

Fig. 1(a) shows the schematic illustration of a pearlite lamellar model employed in this study. The profile of the entire model is a rectangular plate and it consists of five layers. The dimension of the model is $L\times7L$.The central lamellar is cementite (θ). Ferrite (α) lamellar and other cementite are stacked alternately in y-direction. The cementite and ferrite lamellar thickness are denoted as d_θ and d_α, respectively. To imitate possible geometrical non-uniformity in the real structure of pearlite [4], the mid-part of the central layer of cementite is slightly thinned. We construct two models with thickness ratio of ferrite to cementite lamellar $d\alpha/d_\theta$=0.375 and 1.5.

Fig. 1(b) shows the schematic illustration of two-colony pearlite model which is consist of two lamellar structures, colony 1 and colony 2. The profile of the entire model is a rectangular plate and the dimension is $L\times2L$. Lamellar orientation in colony 1 is always perpendicular to the tensile direction, while that in colony 2 makes an angle of φ to lamellae orientation in colony 1. The thickness ratio of ferrite to cementite lamellar in the colony model is $d\alpha/d_\theta$=2. We construct three models with φ=30°, 45° and 60°. These models resemble the pearlite specimen in experimental study [3].

The Young's modulus and Poisson's ration of ferrite are 200 GPa and 0.3, respectively. Stress-strain relationship is determined by experimental data [6] which is defined by the swift equation [7] given as follows:

$$\sigma = a\left(b+\varepsilon^{(p)}\right)^n \tag{2}$$

where σ and $\varepsilon_{xx}^{(p)}$ denote as stress and plastic strain, respectively, whereas a, b and n are constants. We assume a=493, b=0.002 and n=0.28. The Young's modulus and yield strength of cementite are 181 GPa and 2.75 GPa [8] respectively. The Poisson's ratio of cementite is assumed to be 0.3. When this material is deformed by uniaxial tensile load, the elastic strain at the yield point is about 1.5193%.

Analyses are performed with two-dimensional plane stress state with a large deformation framework. The quadrilateral 8-node elements are applied so that the models are divided into nearly square finite elements which size was approximately one-eighth of the lamellar thickness. Total number of the elements for a model is approximately 3×10^4. A uniform tensile displacement was given to the nodes on the lateral surfaces at $x=\pm L/2$.

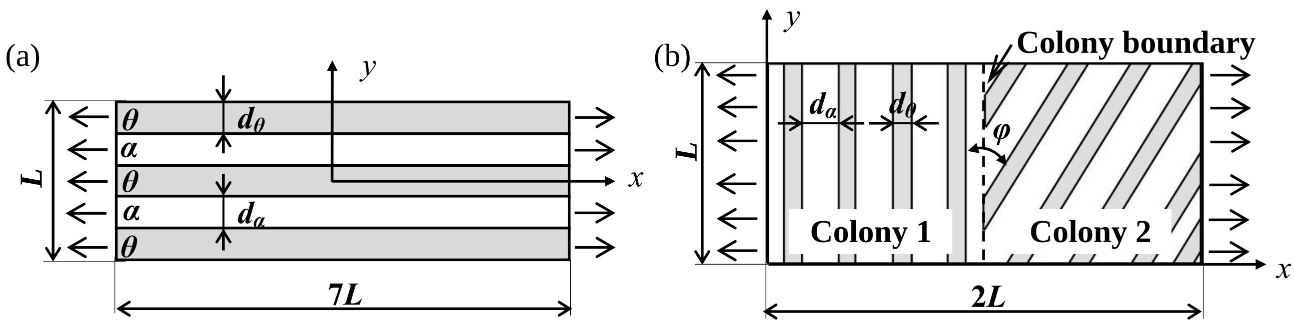

Fig. 1 Schematic illustration of (a) pearlite lamellar model and (b) two-colony model.

Results and Discussion

Deformation of Lamellar Structure. Fig. 2 shows the distributions of the plastic strain component, $\varepsilon_{xx}^{(p)}$ in (a, c) cementite and (b, d) ferrite layer when the nominal tensile strain is 1.527%. The ratios of ferrite lamellar thickness $d\alpha$ to cementite lamella thickness d_θ are (a, b) $d\alpha/d_\theta$=0.375 (d_θ>$d\alpha$) and (c,

d) 1.5 ($d\alpha > d_\theta$), respectively. When the ferrite lamellae are thinner than cementite lamellae, a shear band is formed through the model. On the other hand, when the ferrite lamellae are thicker than cementite lamellae, the shear band is completely suppressed even though the plastic strain in the ferrite layers becomes higher in narrow region than that in the case $d\alpha/d_\theta$=0.375.

Fig. 3 shows the numerical results of nominal stress vs. nominal strain relations obtained for the lamellar models with the ratios of $d\alpha/d_\theta$=0.375 and $d\alpha/d_\theta$=1.5. The model with the ratio $d\alpha/d_\theta$=0.375 shows higher young's modulus and yield stress than the model with the ratio $d\alpha/d_\theta$=1.5. However, the ratio $d\alpha/d_\theta$=0.375 shows sudden drop of nominal stress just after the yield point, while the drop for the model with the ratio $d\alpha/d_\theta$=1.5 becomes gradual. These results indicate that plastic deformation of cementite lamellae was stabilized by increasing the lamellar thickness of ferrite than that of cementite. The reason for the stabilization by increasing the lamellar thickness ratio is attributed to the increase of plastic strain in ferrite layer shown in Fig.2 (d) because the yield stress of ferrite is lower than that of cementite.

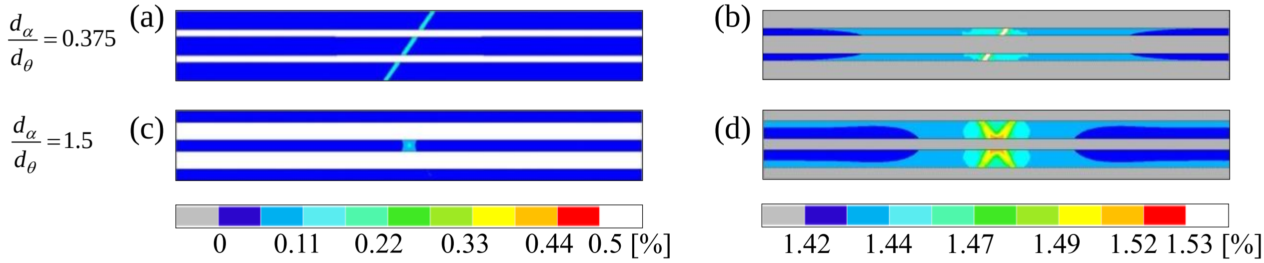

Fig. 2 Distributions of plastic tensile strain component, $\varepsilon_{xx}^{(p)}$ within (a, c) cementite and (b, d) ferrite layer when the nominal tensile strain is 1.527%. The ratios of ferrite lamellar thickness, $d\alpha$ to cementite lamellar thickness, d_θ are (a, b) $d\alpha/d_\theta$=0.375 and (c, d) $d\alpha/d_\theta$=1.5.

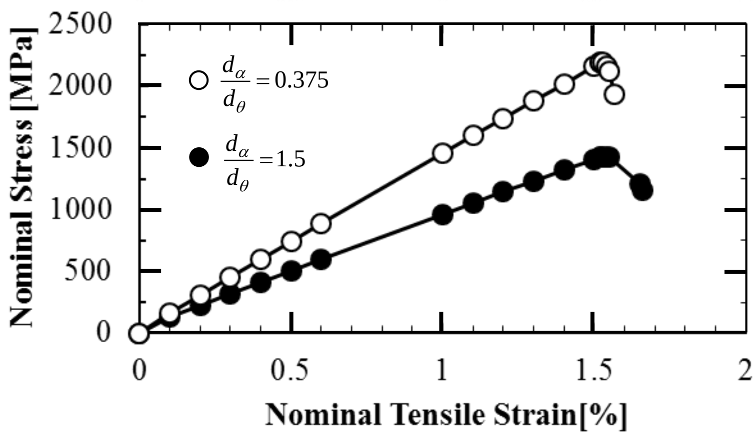

Fig. 3 Load-elongation curves of the lamellar structure models with the ratios $d\alpha/d_\theta$=0.375 and $d\alpha/d_\theta$=1.5.

Deformation of Two-Colony Structure. Fig. 4 shows the distributions of plastic strain component $\varepsilon_{xx}^{(p)}$ in two-colony pearlite model. Differences of the lamellar orientation, φ are (a) 30°, (b) 45° and (c) 60° when the nominal tensile strains are 5, 10, 13 and 18 %. White colored regions indicate that plastic strain is over 80 % and it is found that the high plastic strained band expands in one direction with the increasing of nominal tensile strain. The strain concentration region is different for each model. When the difference of lamellar orientation, φ is smaller than 45°, plastic strain concentrates alongside of cementite lamella as shown in Fig. 4(a). On the other hand, when the difference of lamellar orientation, φ is larger than 45°, plastic strain concentrates around the colony boundary as shown in Fig. 4(c). Therefore, we can confirm the experimental result and prove that the presence of the lamellar orientation degree of which plastic strain tends to concentrates at colony boundaries.

Summary

Fine lamellar and two-colony structures of pearlite consisting of cementite and ferrite layers were modeled and their elasto-plastic deformations were analyzed by the two-dimensional finite element method. Results are summarized as follows;

1. Plastic deformation of cementite lamellae in fine lamellar structure was stabilized by increasing the thickness of ferrite lamellae than that of cementite lamellae.
2. Plastic deformation concentrates around the colony boundary when the difference cementite lamellar alignment between two colonies is larger than 45°.

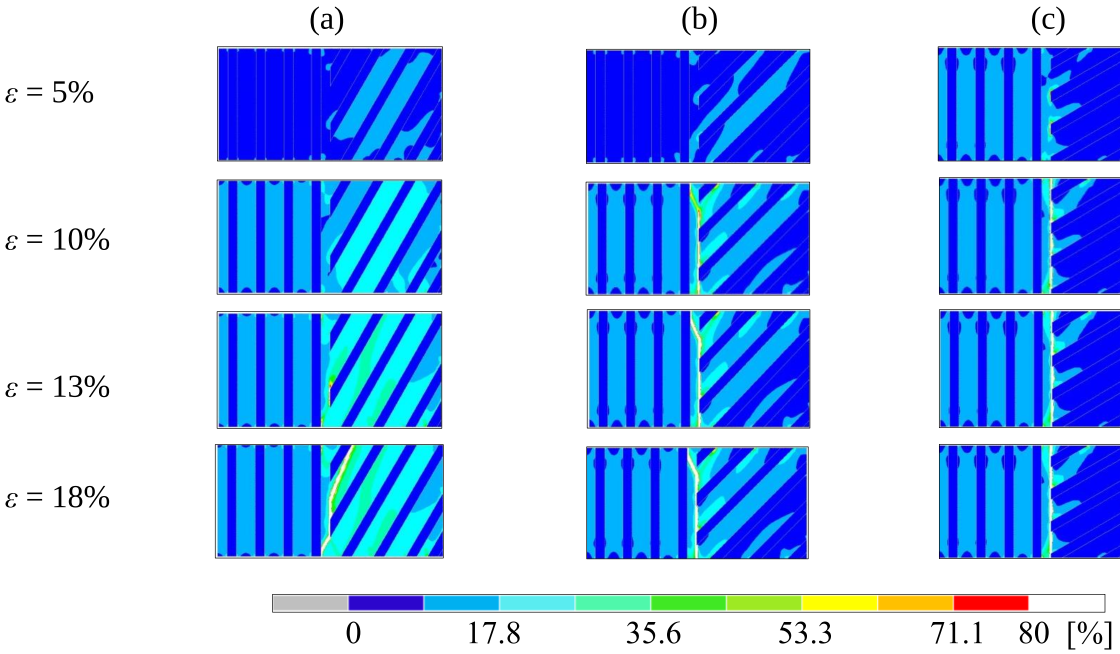

Fig. 4 Distributions of the plastic tensile strain component, $\varepsilon_{xx}^{(p)}$ in pearlite colony. Difference of the lamellar orientation φ is (a) 30°, (b) 45° and (c) 60° respectively when the nominal tensile strains, ε are 5, 10, 13 and 18 %.

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