Strain Localization Effects on Fracture Behavior based on a Physics-based Crystal Plasticity Finite Element Method

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論 文 名　：　Strain Localization Effects on Fracture Behavior based on a Physics-based Crystal Plasticity Finite Element Method（物理に基づいた結晶塑性有限要素法に基づく破壊挙動に及ぼすひずみ局所化の影響）

区　　分　：　甲

論　文　内　容　の　要　旨

During plastic deformation, strain localization will occur in most kinds of metals. It is an important phenomenon that should be paid much attention to for metal applications because strain localization could highly affect mechanical behavior and fracture behavior. From a macroscopic aspect, strain localization affects the mechanical behavior, directly determining the fracture behavior of metals, such as strain hardening, strain softening, and plastic instability. From a microscopic aspect, dislocations pile-up when the dislocation motion is prohibited by barriers such as grain boundaries, inclusions, particles, etc. Dislocation pile-up will make stress concentrate at the tip of the pile-up area, and the stress may become high. Then, the atomic alignment will be disrupted, and the microcrack will nucleate at the tip of the pile-up area. No matter the slip band under uniaxial tensile or persistent slip band (PSB) under cycle loading, plastic strain is concentrated in bands, and a higher plastic strain will have a higher possibility of crack nucleation. Portevin-Le Chatelier (PLC) and adiabatic shear band (ASB) could be considered local plastic instability. Therefore, PLC and ASB could induce the “microscopic necking” inside materials and make crack nucleation.

Traditional fracture mechanics include linear elastic fracture mechanics (LEFM) and elastic-plastic fracture mechanics (EPFM). It can be found that specimens of most fracture behavior research based on LEFM and EPFM have a pre-crack. Therefore, the strain localization around the crack tip should be focused. Once a crack occurs, a strain concentration will be induced and affecting strain localization. Strain localization will not be distributed randomly as in the smooth specimens. It will occur near the crack tip like slip bands, and ASBs. Then, crack propagation will interact between strain concentration and strain localization around the crack tip. Certainly, strain concentration will enhance the strain localization degree. Voids will initiate at the strain localization position (dislocation pile-up, slip band, PSB, PLC, and ASB) ahead of the crack tip. With load increase, the voids will enlarge and merge with cracks. Then, the crack propagates. In other words, strain localization positions decide the path of crack propagation. Moreover, the damage accumulation mode is the primary crack propagation mode for the metal with a high susceptibility to strain localization. This thesis consists of 7 chapters. The outline is as follows.

Chapter 1 described the general introduction of this thesis. Then, brief reviews of strain localization in metals, the correlation between strain localization and fracture mechanics, and the numerical method considering the nature of strain localization were given. Then, issues of strain localization in fracture mechanics that will be solved in this thesis were given in the description of this thesis’s purpose.

Chapter 2 described the numerical model used in this thesis. The kinematics and constitutive equations of crystal plasticity (CP) evolution were given in detail. The connection method of these equations with finite element method (FEM) was briefly described. Furthermore, simulation tools were introduced.

Chapter 3 performed three simulations on a sing-crystal twinning-induced plasticity (TWIP) steel. Firstly, a physics-based crystal plasticity FEM (CPFEM) model incorporating shear banding mechanism for a smooth specimen under tension was established, and a new parameter to quantify strain localization property was proposed. Second, an elastic-plastic FEM (EPFEM) model of a cracked specimen was established to study the strain and stress characteristics ahead of the crack tip without considering strain localization but only strain concentration. Third, a CPFEM model incorporating a shear band mechanism was established to investigate the strain and stress characteristics ahead of the crack tip, considering strain localization and concentration. Finally, a comparison between the results considering only strain concentration and both strain concentration and strain localization shows that the interaction between strain concentration and strain localization was large for long cracks. This chapter solves the first issue.

Chapter 4 continued the quantification work of the strain localization property of metals. A Cu-based single-crystal smooth specimen model was established using the physics-based CPFEM model incorporating a shear band mechanism. The new parameter proposed in the former chapter was modified, and a more suitable word, “Index” was used. Meanwhile, the new index for strain localization susceptibility (SLS) was examined by using “virtual” Cu single crystal specimens with different SLS. Furthermore, a critical material index value was determined to predict the crack behavior. Moreover, the plastic deformation behavior near the crack tip with different material indexes for SLS was discussed. This chapter solves the second issue.

Chapter 5 established a cracked physics-based CPFEM model incorporating a shear band mechanism. Three “virtual” grains were arranged around the crack tip. First, the orientation of these grains was changed to find which one significantly affects the strain distribution ahead of the crack tip under mode I loading. Then, the crack length and the orientation of the grain with the significant effects were changed to study the orientation susceptibility for the strain at and next to the crack tip, and crack tip opening displacement. Finally, a new method was proposed to define the microstructurally-small crack considering strain localization effects. This chapter solves the third issue.

Chapter 6 performed a tensile test for a pure copper smooth specimen to obtain its stress-strain curve. Moreover, a 3D CPFEM model for a smooth specimen was established to fit the material parameters for the pure copper. Then, a notched specimen was processed. First, the grain orientation distribution ahead of the notch tip was measured by electron backscattering diffraction (EBSD). Then, an in situ tensile test was done for the notched specimen. Next, under the same condition of the in situ tensile tests, a 2D plane stress EPFEM for the notched specimen was performed to obtain the deformation status of the measured area. After that, a 2D plane strain CPFEM for the measured area was established from the EBSD results. The boundary conditions were from the deformation status from EPFEM. At last, a comparison of the plastic distribution for the measured area between in situ tensile tests and CPFEM was made. It shows that the physics-based CPFEM incorporating shear band mechanism could simulate the plastic strain distribution for the cases with strain concentration. This chapter solves the fourth issue.

Chapter 7 summarized general conclusions and proposed the outlook.