ABSTRACT

Title: Transformation-thermo-mechanical Analyses on Size Effect in Polycrystalline TRIP Steels based on Crystal Plasticity Finite Element Method

(結晶塑性有限要素法による多結晶 TRIP 鋼における寸法依存性の変態・熱・力学解析)

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Transformation-induced plasticity (TRIP) steels have favorable mechanical properties such as high strength, ductility, and toughness due to strain-induced martensitic transformation (SIMT). At crystal scale, the martensitic transformation (MT) is characterized by the rearrangement of crystal structures with the patterns not only geometrically but also crystallographically. The behavior of crystal lattice with the mode of active slip coupling with MT are dependent strongly on the initial crystallographic orientations and different formed variants. In addition, SIMT phenomenon has a strong relation with the shear band formation at a small length scale. Specifically, strain-induced nucleation with the formation of the microscopic shear bands can provide new sites for the martensitic nuclei. Although the formation of shear bands is at microscopic scale, it possesses features at a larger scale corresponding with inhomogeneous regions occurring due to severe plastic deformation. Up to date, numerical methods become effective to describe the microstructures during MT process including SIMT. In the past, there are numerous numerical models which have been introduced to describe the SIMT behaviors and formed microstructures of materials during MT. Nonetheless, the shear band structures have not been described explicitly so that the nucleation process is still challenged. Therefore, it is still necessary to have a clear investigation on SIMT related to the shear band formation during MT process and deformation behavior at a small length scale of crystalline TRIP steels.

On the other hand, the shear band is formed by the concentration of plastic flow in a band-like structure. The widths of shear bands and the size of martensitic nuclei, which can be considered as length scale effects, obviously influence strongly on SIMT phenomenon and deformation behavior of crystalline materials. Additionally, during plastic deformation, the dislocations, which are associated with length scale effects, are generated inevitably due to the great shear and dilatation in crystal structures. The dislocation networks formed by their heterogeneous distributions can act as obstacles to the gliding movement of other dislocations, and thus providing more hardening for the materials. As a result, a distinctive size-dependent microstructure is provided. Therefore, the plasticity associated with the movement of the dislocations play an important role in not only macroscopic deformation behavior but also

formed microstructure. Although several research works have been included the size effect as the dislocation density to analyze the size-dependent behavior, a clear formulation of the hardening coefficient accounting for size effect in the crystal plasticity theory has not been derived within the finite strain framework yet. Therefore, it is essential to have a good approach to fulfill the power-law model in which the size effect is included in all parameters. Then, the size-dependent crystal plasticity of metastable austenitic steel can be deeply investigated. The dissertation includes the following chapters:

First of all, the development of the numerical models for SIMT in TRIP steels as well as the length scale effect related to the dislocation motions are reviewed in Chapter 1.

In Chapter 2, a computational investigation of microstructure related to SIMT at a length scale of crystal with the formation of shear band structures in both single and polycrystal TRIP steel within the framework of finite strain is presented. The extended framework of the cellular automata approach based on the rate-dependent crystal plasticity finite element method (CPFEM) is provided. A two-dimensional unit cell with periodic boundary conditions (PBCs) for tension is applied to consider the infinite crystalline media. The dependence of the initial crystal orientation is shown. Additionally, the analysis on the length scale effects is shown by modifying the size of a crystal lattice in the monocrystal model and by comparisons of different numbers of grains formed by Voronoi tessellation in the polycrystal model.

In Chapter 3, in order to explain clearly the importance and complexity of plasticity due to the mechanism of dislocations, an investigation on the size-dependent crystal plasticity is done by developed the model from Chapter 2. The notion of microforce associated with a gradient of a kinematic descriptor is coupled within the CPFEM framework to introduce the size dependency induced by energies. A clear and developed hardening coefficient accounting for size effects in CPFEM framework is presented. The analyses on deformation behaviors and formed microstructures of infinite crystal model of both single and polycrystal metastable austenitic steel are numerically presented. From the obtained results, multiple length scale effect including grain size dependence are discussed comprehensively.

Finally, in Chapter 4, the main findings, conclusions, and the required further works are described.