Investigating the plastic deformation mechanisms of a twinning-induced plasticity steel using advanced transmission electron microscopy

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論 文 名： Investigating the plastic deformation mechanisms of a twinning-induced plasticity steel using advanced transmission electron microscopy（先端透過電子顕微鏡法を用いた双晶誘起塑性鋼の塑性変形機構の解明）

Abstract

This dissertation aims to enhance the current knowledge of plastic deformation mechanisms in an Fe-22Mn-0.6C (wt.%) twinning-induced plasticity (TWIP) steel using advanced transmission electron microscopy (TEM). The three main topics treated are 1) the microstructural factors dictating deformation mechanisms in the TWIP steel with ultrafine-grained (UFG) structures, 2) the effect of grain size on the dissociation behavior of dislocations, and 3) the seeking for proof of dislocation pinning. A combination of ex-situ and in-situ TEM deformation techniques, along with post-mortem dislocation analysis was employed throughout the dissertation.

To investigate the microstructural factors influencing deformation mechanisms in the TWIP steel with UFG structures, structural defects in the 2.0 μm and 0.86 μm average grain-sized specimens were investigated by an ex-situ deformation approach (post-mortem) utilizing scanning transmission electron microscopy (STEM) and TEM techniques. The alternation of deformation mechanisms from dislocation gliding and tangling to stacking faults and deformation twinning when the grain size becomes around or smaller than 1 μm was observed. In addition, the nucleation of stacking faults and deformation twins in under 1 μm sized grains was influenced by the grain orientation (Schmid factor). The potential impacts of these deformation mechanisms on plastic deformation behavior and mechanical properties were discussed.

The effect of grain size on deformation twinning was further elucidated by looking into the dissociation behavior of dislocations in specimens with average grain sizes of 8.4 μm and 0.86 μm using an in-situ TEM deformation technique. Wide stacking faults emitted

from grain boundaries were directly observed in grains smaller than 1 μm. The role of grain boundary on the dissociation behavior of dislocations was quantitatively discussed based on the forces acting on the leading and trailing Shockley partial dislocations. A formula for estimating the stress required to emit a partial dislocation from a grain boundary was established. This emission stress strongly depended on the grain orientation, i.e., the difference of the Schmid factor for the leading and trailing partial dislocations. The stresses required to nucleate deformation twins in the grain interior and from the grain boundary were estimated and compared, which helps explain the twinning behavior in TWIP steels across all grain sizes.

To obtain proof of dislocation pinning in the current interstitial solute, carbon (C), containing TWIP steel, the kinetic behavior of dislocations under external tensile stress was investigated using the in-situ TEM deformation technique. A unique dislocation glide observed in the present alloy differs from the dislocation glide observed in other alloys. The dislocations glided while forming straight parts at one or two ends of their lines, indicating the presence of dislocation pinning. The majority of pinned segments had a large edge character and were located near the specimen's foil surface. By analysing the character dependence of dislocation-solutes interaction and solute diffusivities in thin foil, the pinning of dislocations was suggested to be caused by a Cottrell atmosphere. The potential mechanisms for plastic instabilities resulting from the unique dislocation glide were discussed.

The novelty of this work is the comprehensive demonstration of deformation mechanisms in UFG TWIP steel using advanced TEM. The effects of grain size and orientation on twinning behavior were experimentally elucidated using ex-situ and in-situ approaches with thorough and quantitative analyses. The unique dislocation glide indicating dislocation pinning was also discovered. These findings deepen the current knowledge of plastic deformation mechanisms in TWIP steel and have substantial implications for the development of high-strength materials with exceptional ductility.