Mechanics of Dislocation-Precipitate-Grain Boundary Interactions in Aluminum Alloys: An Analytical Approach

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Abstract

The mechanical behaviour of precipitation-hardened aluminium alloys is intricately governed by the interactions among dislocations, precipitates, and grain boundaries, which collectively define their strength, ductility, and resistance to deformation. Dislocations, as carriers of plastic deformation, encounter barriers such as precipitates and grain boundaries that alter their motion and distribution, thereby enhancing the mechanical properties of the material. This study develops an analytical framework to explore the equilibrium configurations of two symmetric edge dislocations located near elliptical precipitates and a grain boundary containing a disclination dipole.

The model considers two semi-infinite grains with identical elastic properties, shear modulus and Poisson's ratio, separated by a grain boundary containing a disclination dipole characterized by its strength and length. Elliptical precipitates, described by their dimensions and misfit strain, are symmetrically embedded in both grains. The equilibrium positions of the dislocations are determined by minimizing the elastic energy of the system, which is influenced by the stress fields generated by dislocations, precipitates, and the grain boundary disclination dipole. The analysis incorporates the Peach-Koehler force to calculate the energy variations and identify stable configurations.

The results highlight the significant impact of microstructural parameters, including the strength and length of the disclination dipole, precipitate morphology, and misfit strain, on dislocation equilibrium and mobility. Specifically, increasing the disclination dipole strength modifies the interaction fields, causing dislocations to either align near the grain boundary or repel into positions within the grains, depending on the eigenstrain magnitude. Additionally, the elliptical geometry of the precipitates introduces anisotropic stress fields that create a complex landscape of attractive and repulsive forces influencing dislocation motion.

This study provides a detailed theoretical understanding of the coupled effects of dislocation-precipitate-grain boundary interactions in precipitation-strengthened aluminium alloys. Explaining these mechanisms contributes to optimizing alloy microstructures to achieve superior mechanical performance. The findings are expected to inform the design of advanced materials through tailored microstructural configurations, enabling better control over strength, ductility, and other critical properties.

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