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Stress–strain behavior of ferrite and bainite with nano-precipitation in low carbon steels

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Abstract—We systematically investigate stress–strain behavior of ferrite and bainite with nano-sized vanadium carbides in low carbon steels; the ferrite samples were obtained through austenite/ferrite transformation accompanied with interphase precipitation and the bainite samples were via austenite/bainite transformation with subsequent aging. The stress–strain curves of both samples share several common features, i.e. high yield stress, relatively low work hardening and sufficient tensile elongation. Strengthening contributions from solute atoms, grain boundaries, dislocations and precipitates are calculated based on the structural parameters, and the calculation result is compared with the experimentally-obtained yield stress. The contributions from solute atoms and grain boundaries are simply additive, whereas those from dislocations and precipitates should be treated by taking the square root of the sum of the squares of two values. Nano-sized carbides may act as sites for dislocation multiplication in the early stage of deformation, while they may enhance dislocation annihilation in the later stage of deformation. Such enhanced dynamic recovery might be the reason for a relatively large elongation in both ferrite and bainite samples.

Keywords: Nano-precipitation; Vanadium carbide; Interphase precipitation; Aging; Mechanical property

1. Introduction

Strength and other mechanical properties of metals and alloys are designed by controlling lattice defects in crystals. Crystal defects that affect the mechanical properties of materials are mainly dislocations, solute atoms, precipitates and grain boundaries, all of which generally act as obstacles for dislocation movement during deformation at relatively low temperature, leading to an increase in strength of materials. Strengthening by dislocations, solute atoms, precipitates and grain boundaries are termed dislocation strengthening, solid solution strengthening, precipitation strengthening and grain boundary strengthening, respectively. Among these strengthening mechanisms, much attention has recently been paid to precipitation strengthening in steel production.

It is well known that precipitation strengthening by undeformable hard particles increases inversely proportional to the average inter-particle spacing, according to the Orowan mechanism [1]:

$$\tau_{ppt} \propto \frac{Gb}{L}\ \text{(MPa)} \tag{1}$$

where τ_{ppt} is the contribution from precipitation strengthening in shear stress, G is the shear modulus, b is the Burgers vector and L is the inter-particle spacing. Note that the inter-particle spacing L is an increasing function against the average radius of particles or a decreasing function against the volume fraction of particles [2] (see also Eq. (15) in this paper). In other words, a decrease in average size or an increase in volume fraction of particles leads to an increase in precipitation strengthening in the Orowan-type precipitation strengthening. However, too much addition of expensive alloying elements to obtain high volume fraction of particles unwantedly results in a significant increase in the production cost. Therefore, dispersion of nano-sized precipitates, or nano-precipitation (see e.g. Refs. [3,4]), is a promising strategy to maximize precipitation strengthening with minimizing the addition of alloying elements. This is one of the main reasons why nano-precipitation has

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