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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

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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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recently received much attention in the production of high-strength steels.

In carbon steels containing strong carbide-forming elements, such as niobium, titanium and vanadium, nano-sized alloy carbides can be formed and dispersed into the matrix during heat treatments, either by interphase precipitation or by tempering of martensite and bainite. In interphase precipitation [5–9], nano-sized alloy carbides are nucleated on austenite/ferrite interfaces during ferrite transformation from austenite, typically leaving a periodic array of alloy carbides in the ferrite. One of the advantages of interphase precipitation is that high-strength ferrite steels can be produced directly during cooling from austenite at high temperature, so that subsequent heat treatment is not necessary, i.e. heat treatment cost can be reduced, unlike quenched martensite steels that require tempering. Low and medium carbon steels with interphase precipitated carbides are known to show high strength and good formability, so that such steels have been in practical use, mainly as automobile body parts [10–13]. On the other hand, high-temperature tempering of martensite or bainite in alloy steels can also produce precipitation of nano-sized alloy carbides, leading to an increase in strength during tempering, which is called secondary hardening [14–19]. Secondary hardened martensite or bainite steels have also been used widely in industrial applications, such as tool and die steels or automobile products, because of its ultrahigh strength and sufficient toughness.

Although steels containing nano-sized alloy carbides have widely been used in commercial applications, the effect of nano-sized alloy carbides on mechanical properties is still unclear. This study will focus on the effect of nano-sized carbides on strength and ductility in different ferrite matrices. Fig. 1 schematically shows microstructures obtained by interphase precipitation (a), and by aging of martensite or bainite (b), both containing nano-sized alloy carbides. In interphase precipitation (Fig. 1a), nano-sized carbides are precipitated in the matrix of polygonal ferrites with a low density of dislocations. On the other hand, in aging of martensite or bainite (Fig. 1b), nano-sized carbides are dispersed in elongated martensite lathes or bainitic ferrites with high density of dislocations. The effect of nano-sized alloy carbides on the mechanical properties of materials could be different between these two cases, but details are not yet understood very well.

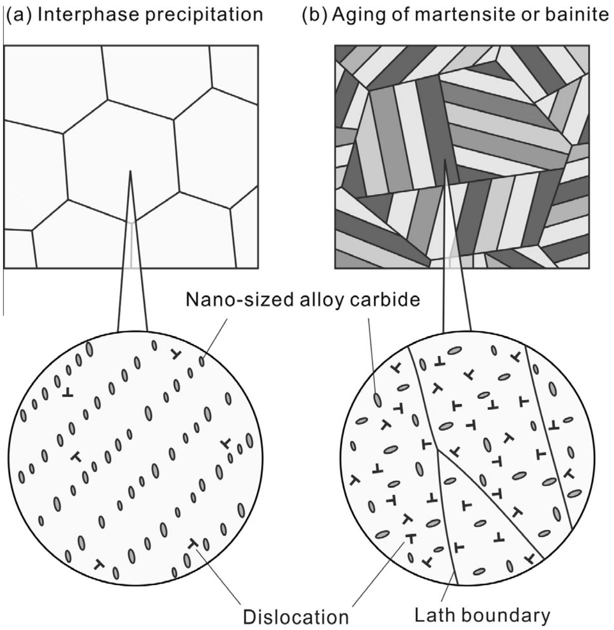

Fig. 1. Schematic illustration of microstructures obtained by interphase precipitation (a) or by aging of martensite or bainite (b).

In the present study, therefore, ferrite and bainite structures with nano-sized carbides are prepared using a low carbon steel containing a small amount of vanadium. Uniaxial tensile tests are systematically carried out at room temperature, and the effect of nano-precipitates on yield stress, work hardening and ductility is discussed in detail.

2. Experimental

A low carbon steel with a chemical composition of Fe–0.10C–0.22Si–0.83Mn–0.014P–0.014S –0.003 N–0.001Ti–0.288V (in mass%) was used in the present study. From thermodynamic calculation by Thermo-Calc software, the following temperatures were obtained: vanadium carbide (VC) solution temperature of 1077 °C, Ae_3 temperature of 852 °C and Ae_1 temperature of 713 °C in para-equilibrium. A cast ingot of the steel prepared by vacuum melting was hot-rolled at the finish rolling temperature of ~940 °C. Hot-rolled samples were homogenized in Ar atmosphere at 1180 °C for 24 h, and were used as starting materials. The starting materials were heat-treated in a vacuum furnace at 1200 °C for 600 s for austenitization and solution treatment, and immediately isothermally transformed at 690 °C or 600 °C in a salt bath for different holding periods in the range from 20 s to 172.8 ks (48 h), followed by water quenching. The isothermal treatment temperature of 690 °C was chosen to obtain ferrite structure with interphase precipitation of nano-sized VC particles, while the temperature of 600 °C was chosen to obtain bainite structure with precipitation of VC particles by aging.

Microstructures of the obtained samples were characterized by optical microscopy, electron backscatter diffraction (EBSD) in a scanning electron microscope (SEM) and transmission electron microscopy (TEM). Longitudinal sections perpendicular to transverse direction (TD) (TD planes), including rolling direction (RD) and normal direction (ND), of the hot-rolled sheets were prepared for the observations. For optical microscopy and EBSD measurements, TD planes were mechanically polished by SiC emery papers, diamond paste and then colloidal silica to obtain mirror surfaces, followed by etching in a solution of 3 vol.% HNO_3 (nitric acid) + 97 vol.% C_2H_5OH (ethanol). EBSD measurements were carried out in an FEI Quanta 3D SEM using a program TSL OIM Dara Correction. The obtained data were analyzed using a program TSL OIM Analysis. For TEM observations, thin foils parallel to TD planes were mechanically polished by SiC emery papers and then electro-polished in a solution of 10 vol.% $HClO_4$ (perchloric acid) + 90 vol.% C_2H_5OH (ethanol) at −15 °C at a voltage of 40 V. Conventional bright field (BF) and dark field (DF) images were taken by an FEI CM300 TEM operating at 300 kV. Dislocation density in the samples was determined from TEM images taken under multi-beam diffraction conditions to reveal all dislocations, where the thickness of the TEM foils was measured by the convergent beam electron diffraction technique. High resolution TEM observation was also carried out in an FEI Titan 300 operating at 300 kV, to observe atomic structures of ferrite matrix and precipitates.