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High tensile ductility and high strength in ultrafine-grained low-carbon steel

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ABSTRACT

High tensile ductility and high strength were simultaneously obtained in UFG low-carbon steel prepared by appropriate annealing of cold-rolled martensite–ferrite dual-phase structure. High tensile ductility and high strength are attributed to the coexistence of fully recrystallized ferrite grains with bimodal size distribution and dispersive nanoscale carbides.

1. Introduction

Based on the Hall–Petch relationship, decreasing the grain size can markedly increase the yield strength. However, high yield strength is usually achieved at the expense of the ductility and uniform elongation due to the little strain hardening after yielding [1]. Strain hardening process is related with the accumulation and interaction of dislocations. However, UFG metals obtained by the severe plastic deformation usually have a high initial dislocation density or even up to the saturation, which results in very low strain hardening rate and poor ductility during subsequent deformation [1,2]. Moreover, the weak interaction of dislocations existed in UFG metals due to the short free path of the dislocation movement also causes very low strain hardening rate.

Some reports have showed that the ductility of several nanograin/UFG nonferrous metals can be enhanced without much strength loss by tailoring microstructures to bimodal grain size distribution (BGSD) [1–5]. Zhao et al. [6] proposed a strategy to simultaneously increase the ductility and strength of bulk nanostructured 7075 Al alloy using very small nanoscale second-phase precipitation. Accordingly, a combination of BGSD and nanoscale second-phase precipitation would be a more effective method for the enhancement of the ductility without much strength loss in UFG metals.

Recently, Azizi-Alizamini et al. [7] reported that BGSD-UFG ferrite and carbide particles were prepared in low-carbon steel through fully quenching followed by intercritical quenching, and then 50% cold rolling and long term annealing at low temperature (annealing at 525 °C for 1200 min). The BGSD ferrite microstructure was composed of fine grains with size below 2 μm and volume fraction of ~40% and coarse grains with sizes of 3–15 μm and volume fraction of ~60%. The uniform elongation of about 14% was achieved, but the tensile strength, ~550 MPa, was not so high. Additionally, Okitsu et al. [8] fabricated fully annealed UFG ferrite grains and homogenously dispersed cementite particles in low-carbon steel by 91%-reduction cold rolling of a martensite–ferrite duplex microstructure containing ~42% (volume fraction) martensite and short time annealing at high temperatures (annealing at 655 °C for 2 min). They obtained the high yield strength of 658 MPa, high tensile strength of 672 MPa, very low uniform elongation of 4.1%. In view of results cited above, we can expect that high uniform elongation and high tensile strength will be simultaneously obtained in UFG low-carbon steels on condition that the cold-rolled dual-phase microstructure is annealed at appropriate temperature for appropriate time.

The aim of the present paper is to prepare high-uniform-elongation and high-strength UFG low-carbon steel through tailoring microstructure to duplex-sized recrystallized ferrite grains composed of submicron and several micron grains coupled with dispersively nanoscale carbides by appropriate annealing of cold-rolled dual-phase microstructure.

2. Experimental procedure

A low-carbon steel was used in this study and supplied as hot rolled plate with the composition of 0.12 C, 0.24 Si, 1.42 Mn, 0.012 P, 0.004 S and 0.014 Nb (wt.%). The sample with size of 120 mm × 30 mm × 7 mm was cut from the plate by wire electrode

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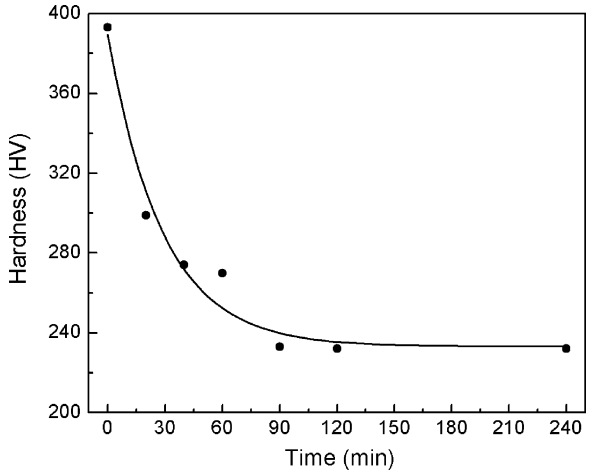

Fig. 1. Hardness–time curve for sample annealed at 560 °C for different times.

discharging, making the longitudinal direction parallel to rolling direction (RD), austenized at 1000 °C for 30 min and furnace cooled down to 760 °C holding 30 min, and rapidly quenched into brine to obtain martensite–ferrite dual-phase structure. The quenched sample was cold rolled by a 64% reduction in six passes with a laboratory two-high rolling mill (roll diameter 210 mm), then annealed at 560 °C for different times. According to the method described in Ref. [9], we determine that the recrystallization is just complete when annealing for 90 min based on the hardness–time curve (Fig. 1). Microstructural examinations were carried out on a S-4800 field emission scanning electron microscope (SEM) operated at 25 kV and a Hitachi H-800 transmission electron microscope (TEM) operated at 200 kV. SEM samples were prepared by mechanical grinding, polishing, and etching with 3% Nital. TEM samples were prepared by cutting into ~0.5-mm-thickness slices using wire electrode discharge machine and mechanical grinding down to ~30 μm in thickness, and then thinning to perforation by ion-beam milling on a 691 Precision Ion Polishing System. All microstructures were examined from the transverse direction of the rolled plate. Tensile stress–strain curve was measured on a Gleeble 3500 thermomechanical simulator at room temperature and a strain rate of 10^{-3} s^{-1} by using a set of specially designed holder. Dog-bone-shaped samples with gauge length 20 mm, width 2 mm and thickness 1 mm were used for tensile test, and the tensile axis was parallel to RD.

3. Results and discussion

Fig. 2a presents the SEM micrograph of the sample processed by heating to 1000 °C for 30 min and furnace cooling down to 760 °C for 30 min followed by rapid quenching into brine, showing martensite–ferrite dual-phase structure with ~60 vol.% martensite and ~40 vol.% ferrite. Fig. 2b reveals the TEM micrograph of the sample processed by 64%-reduction cold rolling of the dual-phase structure. One can see that the plastic deformation occurred in both martensite and ferrite. Ferrite grains were elongated roughly along the RD and curved. Laths of martensite were bent and roughly turned to the RD. High-density dislocations were generated inside ferrite grains and martensitic laths, making the ferrite grains and martensite laths subdivide into "cells" with the random lattice orientation for which the diffraction rings give the evidence as shown in the inset of Fig. 2b. This was caused mainly by bend and shear deformation that easily occurred in the process of cold rolling of the dual-phase structure composed of hard martensite and soft ferrite.

The SEM image of the microstructure in the sample subjected to 64%-reduction cold rolling and annealing at 560 °C for 90 min is shown in Fig. 3a. It can be seen that the microstructure comprises coarse and fine ferrite grains (BGSD ferrite grains) dispersed with nanoscale cementite particles. In Fig. 3a, coarse ferrite grains can be revealed, and fine grains cannot be distinguished. Therefore, the fine grain structure was examined by means of TEM. The typical microstructure and the corresponding diffraction pattern are shown in Fig. 3b and its inset, respectively. Both fine and coarse grains are equiaxial and little dislocations inside them, indicating completely recrystallized grains. The mean sizes of coarse grains and fine grains in the annealed microstructure were estimated to be ~5.0 μm and ~0.7 μm by extensive SEM and TEM observations, respectively. The fraction of the coarse grain was also estimated to be ~40 vol.% by SEM. Actually, the volume fraction of the fine and the coarse grains can be roughly scaled based on the volume fraction of the martensite and ferrite in the initial dual-phase structure [7]. TEM observations also reveal that the cementite particles with size below 100 nm (mean size ~60 nm) mainly existed in the fine grain region. These nanoscale carbides precipitated at grain boundaries and inside ferrite grains in company with recovery and recrystallization during the annealing of the deformed martensite, since large numbers of defects induced by plastic deformation of

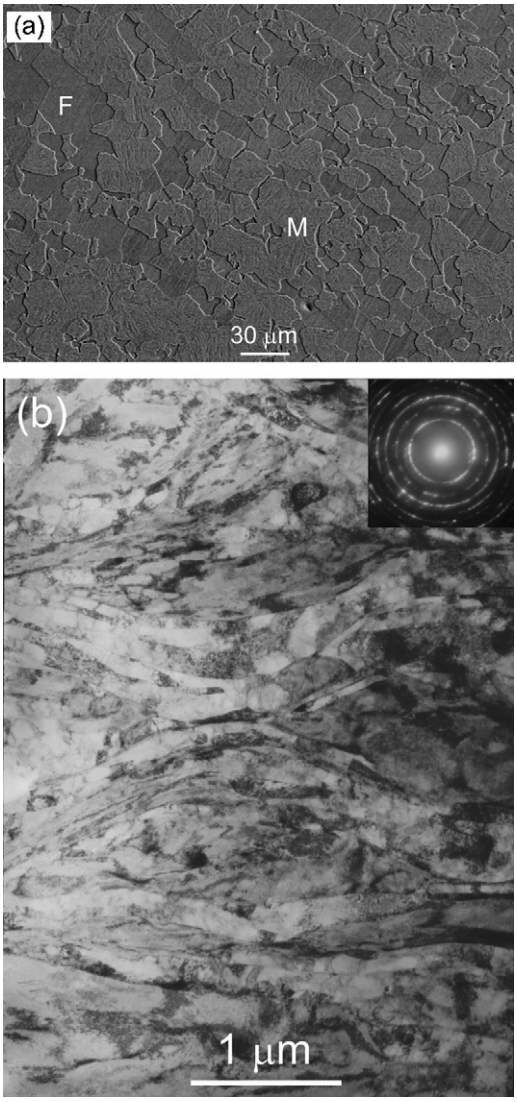

Fig. 2. (a) SEM micrograph of sample processed by heating to 1000 °C for 30 min and furnace cooling down to 760 °C for 30 min followed by rapid quenching into brine. (b) TEM image of microstructure after 64%-reduction cold rolling of dual-phase structure.