Materials Science and Engineering A 552 (2012) 204–210

Contents lists available at SciVerse ScienceDirect

Materials Science and Engineering A

journal homepage: www.elsevier.com/locate/msea

Annealing softening behaviour of cold-rolled low-carbon steel with a dual-phase structure and the resulting tensile properties

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ARTICLE INFO

Article history:
Received 29 September 2011
Received in revised form 16 February 2012
Accepted 12 May 2012
Available online 18 May 2012

Keywords:
Mechanical characterization
Steel
Bulk deformation
Grain refinement

ABSTRACT

The softening behaviour of cold-rolled dual-phase low-carbon steel during annealing and the resulting microstructure and tensile properties were investigated. Ferrite–martensite dual-phase structures were produced by intercritical heat treatments (IHT): (A) intercritical quenching at 760 °C after quenching at 1000 °C; (B) furnace cooling from 1000 to 760 °C and immediate quenching. The results show that an excellent strength–ductility balance is achieved by the cold rolling and appropriate annealing of these two IHT samples. Completely recrystallized ultrafine-grained ferrite with a bimodal distribution and dispersively nanoscale carbide particles are obtained. The annealing softening activation energy of cold-rolled sample (A) is far less than that of cold-rolled sample (B). In addition, the effect of IHT on the softening behaviour, resulting microstructure and tensile properties was discussed.

1. Introduction

The fabrication of ultrafine-grained (UFG) materials has been paid extensive attention since grain refinement can simultaneously improve the strength and toughness of metallic materials. Severe plastic deformation (SPD) is an effective method to produce UFG or even nanoscale structures. However, SPD is difficult for use in the mass production and large-dimension sample fabrication of UFG materials, because of the requirement of a very large plastic strain and special equipment. Furthermore, UFG metals obtained by SPD usually have a very low strain hardening rate and poor tensile ductility [1,2]. This restricts their application as structural materials. Ma [3] reviewed routes to improve the tensile ductility of bulk nanostructured metals and alloys. Some research shows that the bimodal grain size distribution (BGSD) [1,2,4–6] and nanoscale second-phase precipitates [7] have been successfully used for improving the ductility of nanograin/UFG metals. Song et al. [8] reported that finely dispersed globular cementite is beneficial in improving strength and ductility by enhancing the work hardening rate of UFG steels. Accordingly, a combination of BGSD and nanoscale second-phase precipitation would be a more effective method for the enhancement of the ductility without a large amount of strength loss in UFG metals. In recent years, some researchers have reported on a martensite processes for fabricating UFG structures in low-carbon steels [8–13]. These processes are based on cold deformation plus annealing or the warm deformation of martensite or martensite–ferrite. The deformation can be conducted on a conventional rolling mill rather than with special equipment, and it has no need of very large plastic strains as required by SPD. Among these processes, the annealing of deformed martensite–ferrite [10,14,15] and the warm deformation of martensite–ferrite [12] can produce BGSD UFG ferrite and dispersively nanoscale carbrides, achieving an excellent balance in strength–ductility [12,15]. However, the annealing softening behaviour of deformed martensite–ferrite structure has not yet been reported. The aims of the present work are to study the annealing softening behaviour of deformed martensite–ferrite structure and to discuss the effect of IHT on the resulting microstructure, tensile properties and softening behaviour.

2. Experimental procedure

The low-carbon steel used in this study was supplied as a hot rolled plate with a composition of 0.12 C, 0.24 Si, 1.42 Mn, 0.012 P, 0.004 S and 0.014 Nb (wt.%). Samples with a size of 120 mm × 30 mm × 7 mm were cut from the plate by wire electrode discharging, with the longitudinal direction parallel to the rolling direction (RD). Martensite–ferrite dual-phase structures were prepared by the following intercritical heat treatments (IHT): (A) austenitizing at 1000 °C for 30 min and brine cooling to room temperature, and then intercritical annealing at 760 °C for 30 min and brine cooling to room temperature; (B) austenitizing at 1000 °C for 30 min and furnace cooling to 760 °C for 30 min followed by brine cooling to room temperature. After IHT, samples were cold rolled by a ~64% reduction in 6 passes with a laboratory two-high

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http://dx.doi.org/10.1016/j.msea.2012.05.032

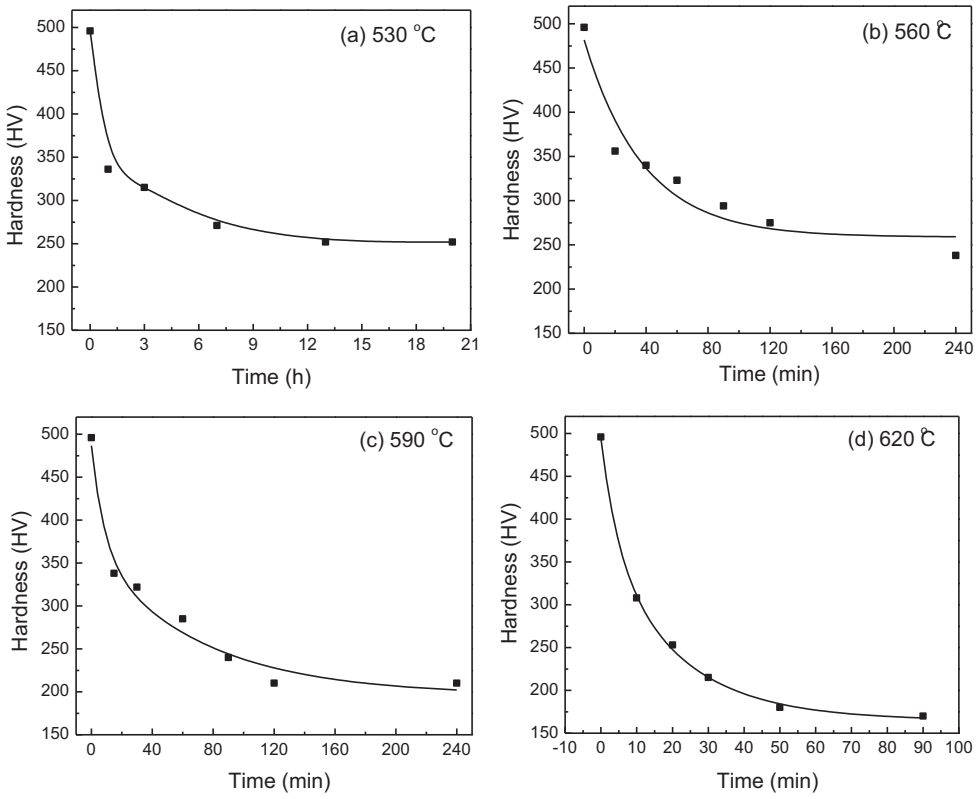

Fig. 1. Hardness–time curves of sample (A) at different annealing temperatures.

rolling mill (roll diameter 210 mm), and then annealed for different periods at 530, 560, 590 and 620 °C. The Vickers hardness of the annealed samples was measured on a HBRV-187.5 sclerometer under a load of 30 kgf in order to explore the softening behaviour during annealing. Microstructural examinations were carried out from the transverse direction of rolled plates by using an S-4800 scanning electron microscope (SEM) and a Hitachi H-800 transmission electron microscope (TEM). SEM samples were prepared by mechanical grinding, polishing, and etching with 3% Nital. TEM samples were prepared by cutting into ~0.5 mm-thick slices using a wire electrode discharge machine and mechanical grinding down to a thickness of ~30 μm, followed by thinning to perforation by ion-beam milling on a 691 Precision Ion Polishing System. Volume fractions of martensite in IHT samples were determined by estimating the area fraction of martensite in SEM micrographs using image process software. The mean grain sizes were measured by the intercept method. Engineering stress–strain curves were measured at room temperature and at a strain rate of $10^{-3}\,s^{-1}$ on a Gleeble 3500 thermomechanical simulator by using a set of specially designed holders and tensile samples with a gauge length of 20 mm, width 2 mm and thickness 1 mm, with the tensile axis parallel to RD.

3. Results

3.1. Softening behaviour

Figs. 1 and 2 show the hardness–time curves of cold-rolled samples (A) and (B) annealed at different temperatures. It is clear that for a given annealing temperature, the hardness decreases as the annealing time is increased. The hardness drop becomes sharper when the annealing temperature is increased.

From Ref. [16], the softening fraction X of cold-rolled steels annealed at a given temperature for different times can be estimated from the hardness:

$$X = \frac{H_0 - H}{H_0 - H_{Rex}} \tag{1}$$

where H_0 is the hardness of the as-cold-rolled sample, H_{Rex} is the hardness corresponding to the completely recrystallized sample, and H is the hardness after a given annealing condition. It has been proved that the softening fraction from hardness measurements can be compared to the recrystallized fraction from quantitative metallography. Hardness measurements can be used to determine the recrystallized fraction using Eq. (1) [16]. Thus, softening is equivalent to recrystallization, and recrystallization equations can be used to express softening.

From the Avrami equation:

$$X = 1 - e^{-Kt^n} \tag{2}$$

where K and n are constants. The following equation can be determined:

$$\ln\ \ln\frac{1}{1-X} = \ln K + n\ln t \tag{3}$$

Combining (1) and (3):

$$\ln\ \ln\frac{H_0 - H_{Rex}}{H - H_{Rex}} = \ln K + n\ln t \tag{4}$$

The annealing softening of plastically deformed metals is a thermal activation process, the relationship between softening rate V_r and annealing temperature T can be given by the Arrhenius equation:

$$V_r = A\ e^{-Q_r/RT} \tag{5}$$

where Q_r is the activation energy of annealing softening, R is the universal gas constant ($8.314\,J\,mol^{-1}\,K^{-1}$) and A is a constant. For a