Materials Science & Engineering A 654 (2016) 359–367

Contents lists available at ScienceDirect

Materials Science & Engineering A

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

Interplay between deformation behavior and mechanical properties of intercritically annealed and tempered medium-manganese transformation-induced plasticity steel

Z.H. Cai [a,*], H. Ding [a], H. Kamoutsi [b], G.N. Haidemenopoulos [b], R.D.K. Misra [c,*]

[a] School of Materials and Metallurgy, Northeastern University, Shenyang 110819, China
[b] Department of Mechanical Engineering, University of Thessaly, Volos, Greece
[c] Department of Metallurgical and Materials Engineering, University of Texas at El Paso, El Paso, TX 79968, USA

ARTICLE INFO

Article history:
Received 1 December 2015
Received in revised form
12 December 2015
Accepted 14 December 2015
Available online 19 December 2015

Keywords:
TRIP steels
Austenite stability
Mechanical properties
Work hardening
Simulations

ABSTRACT

We elucidate the mechanistic contribution of the interplay between microstructural constituents and plastic deformation behavior of a hot rolled Fe–0.18C–10.62Mn–4.06Al–0.03Nb transformation-induced plasticity (TRIP) steel that was characterized by excellent tensile elongation (TE) of 48%, ultimate tensile strength (UTS) of 1012 MPa, and yield ratio of 0.58. The excellent mechanical properties were a cumulative contribution of TRIP effect, discontinuous TRIP effect, and the cooperative deformation of austenite, δ-ferrite, and α-ferrite, such that the austenite stability dictated the ultimate mechanical properties and the dynamic composite nature of the three stages of work hardening. More importantly, the austenite stability was governed by the combination of intercritical annealing and tempering treatment, when partitioning of carbon and manganese took place; an aspect supported by the simulation of intercritical annealing condition via DICTRA. The study underscores the significance of intercritical annealing in conjunction with tempering as a viable route to obtain the desired mechanical properties in the new generation of advanced high strength steels (TRIP steels).

1. Introduction

It is well known that austenite plays a significant role in obtaining excellent combination of strength and ductility in transformation-induced plasticity (TRIP) steels. The microstructure of conventional TRIP steels consists of ferrite as the dominant phase (55–65%), retained austenite (< 20%), bainite (25–35%), and occasionally a small amount of martensite [1–3]. Recent studies [4–8] focused on medium-Mn (5–12%) TRIP steels suggested that superior mechanical properties can be obtained with increase in Mn- and C-content, which increases the volume fraction of retained austenite (20–80%).

An innovative heat treatment, referred as “austenite reversed transformation” (ART), was applied to medium-Mn steels [4–7,9–11]. Retained austenite was obtained by successive enrichment of Mn and C in the reversed austenite during the intercritical process. However, ART-annealing was not applicable to the experimental steel, and quenching and tempering (Q&T) was envisioned by us an alternative and effective heat treatment [12,13]. Tempering is often used to relieve the residual stress. However, it generally leads to the decomposition of retained austenite into ferrite and cementite, which is detrimental to ductility. It was reported that [14,15] the amount of retained austenite was decreased with increase in tempering temperature in steels containing 2 wt% Mn. A large fraction of austenite continued to remain in Fe–0.2C–5Mn (wt%) steel after tempering at 400 °C [16]. The decomposition temperature of austenite increased with increasing Mn content [17], which suggested that the thermal stability of austenite can be enhanced by the enrichment of Mn. Thus, it is possible for austenite in the medium-Mn steels to remain stable during the tempering process. Moreover, it was observed that the precipitation of carbides during tempering led to decrease in the austenite fraction. Thus, Al was added to medium-Mn steels, where the role of Al was to optimize austenite stability by suppressing cementite formation [18].

Austenite stability against mechanically-induced transformation to martensite is known to depend on chemical composition, austenite size, austenite morphology and stress state [12,19]. M_S is the athermal martensite start temperature. The stability of retained austenite can be characterized by M_s^σ temperature, at which the stress required to trigger stress-assisted transformation attains the yield strength [20]. In the $M_S \sim M_s^\sigma$ temperature range, martensite nucleation on existing nucleation sites is enhanced by

* Corresponding authors.
E-mail addresses: tsaizhihui@163.com (Z.H. Cai), dmisra2@utep.edu (R.D.K. Misra).

http://dx.doi.org/10.1016/j.msea.2015.12.057
0921-5093/

stress, i.e. stress-assisted transformation of austenite to martensite takes place. In the $M_s^\sigma \sim M_d$ temperature range, martensite formation occurs on nucleation sites introduced by plastic deformation, such as slip band intersections, where strain induced transformation of austenite to martensite occurs. No transformation takes place at temperatures higher than the M_d temperature. Therefore, austenite stability is influenced by the deformation temperature, and accounts for the different martensite transformation mechanisms (stress-assisted or strain-induced).

From the above discussion, tempering had a significant impact on retained austenite content and stability. To study the effect of mechanism of martensite transformation on mechanical properties, samples with different austenite stability were obtained by tempering at different temperature. The objective of the study is to elucidate the tempering effects on the mechanical properties and deformation behavior of a hot-rolled medium manganese steel.

2. Experimental

The chemical composition of the experimental TRIP steel had a nominal composition of Fe–0.18C–0.62Mn–4.06Al–0.03Nb (wt%). The selected composition is based on the role of alloying elements and an equilibrium thermodynamic analysis that is discussed elsewhere [12]. A 40 kg experimental steel ingot was cast after melting the steel in a vacuum induction furnace. The ingot was heated at 1200 °C for 2 h, hot forged into rods of section size 100 mm × 30 mm, then air-cooled to room temperature. Subsequently, the rods were soaked at 1250 °C for 2 h, hot-rolled to 4 mm thick strip, and finally air cooled to room temperature.

In order to establish appropriate heat treatment schedule, the critical temperatures of Ac_1 and Ac_3 of the experimental steel obtained by dilatometry were 585 °C and 820 °C, respectively. The as-hot-rolled sheets were subjected to quenching and tempering (Q&T) heat treatment for reasons discussed in the introduction section. First, they were soaked in a high temperature furnace at 775 °C for 1 h, and then immediately quenched in water. Second, the quenched samples were tempered at 300 °C, 400 °C, 500 °C, 600 °C for 1 h, respectively, followed by air cooling.

Specimens of 12.5 mm width and gage length of 50 mm were subjected to tensile tests using a universal testing machine (SANSCMT 5000) at a constant crosshead speed of 3 mm min^{-1} at room temperature. Prior to the tensile tests, the uneven surface of the samples was polished. The samples were etched with 25% sodium bisulfite aqueous solution. Microstructural examination was carried out using scanning electron microscope (SEM), electron microprobe analysis (EMPA) and transmission electron microscope (TEM). Austenite volume fraction was determined by X-ray diffraction (XRD) based on the integrated intensities of $(200)_\alpha$, $(211)_\alpha$, $(200)_\gamma$, $(220)_\gamma$ and $(311)_\gamma$ diffraction peaks [21].

The austenite formation and associated solute partitioning during intercritical annealing and tempering were simulated with DICTRA software [22] using the TCFE6 thermodynamic database and the MOBFE2 mobility database for ferrous alloys.

3. Results and discussion

3.1. Microstructure

The SEM micrograph of as-hot-rolled sample quenched from 775 °C is presented in Fig. 1a. Fig. 1b–e describe the microstructure of the quenched samples that were tempered in the temperature range of 300–600 °C. The microstructural constituents comprised of austenite, layered δ-ferrite, and acicular α-ferrite that formed during intercritical annealing. For clarity, the magnified region of ferrite, marked with rectangle in Fig. 1e, is presented in Fig. 1f. The two kinds of ferrite differed in morphology, but also in microhardness (Table 1).

The variation in the volume fraction of austenite obtained from XRD is summarized in Fig. 2c. The austenite content in the untempered sample and samples tempered in the range of 300–500 °C was essentially similar, except for a small decrease in the sample tempered at 600 °C. Based on the SEM micrographs and

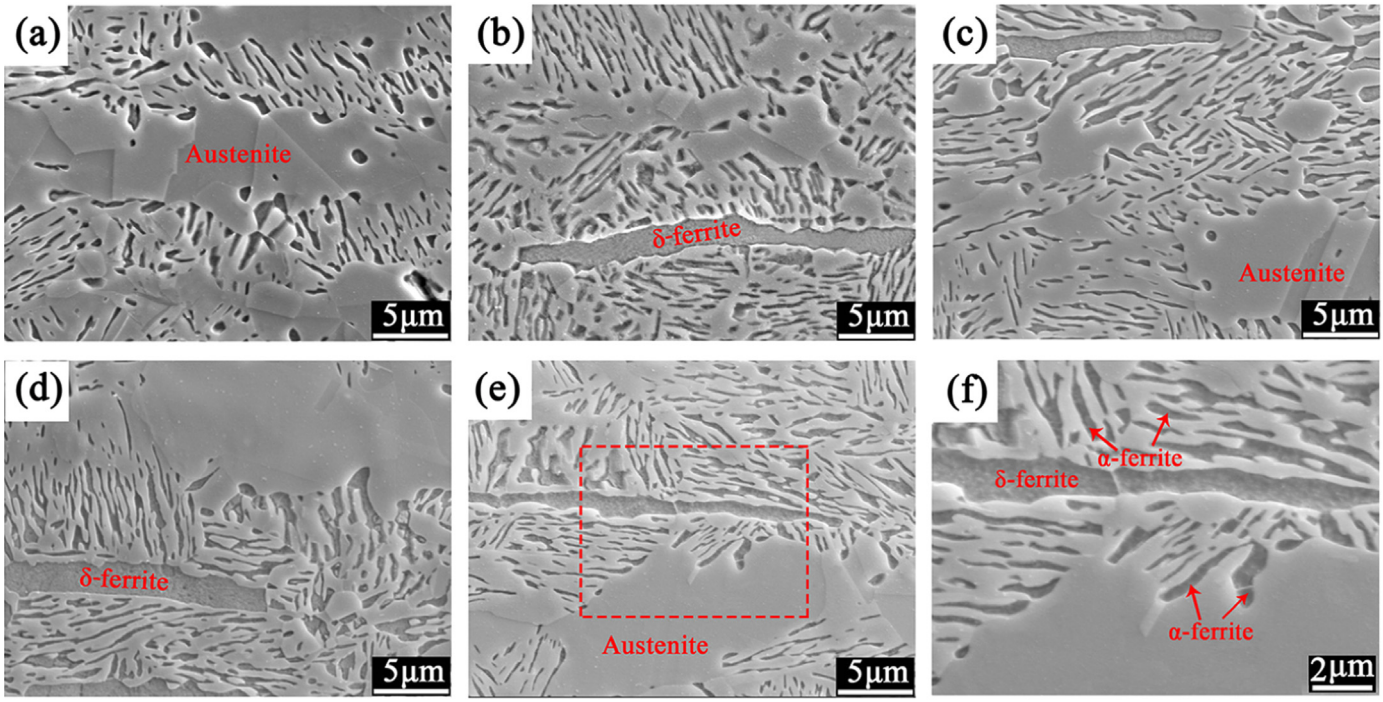

Fig. 1. SEM micrographs of samples quenched from 775 °C and then tempered at different temperatures. (a) Untempered, (b) 300 °C, (c) 400 °C, (d) 500 °C, (e) 600 °C, and (f) higher magnification of the boxed region in (e).