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The influence of microstructural characteristics on yield point elongation phenomenon in Fe-0.2C-11Mn-2Al steel

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ABSTRACT

We elucidate here the underlying reasons for the yield point elongation (YPE) phenomenon in medium-Mn steel. The cold-rolled Fe-0.2C-11Mn-2Al steel was subjected to controlled annealing temperature and soaking time such that YPE of different lengths was obtained. It was observed that the ultra-fine grained or globular microstructure is not the critical factor responsible for YPE. YPE is a consequence of close competition between the work hardening (via martensitic transformation) and softening (by stress relaxation and transfer) induced by the TRIP effect. The ferrite grains with γ fiber have the potential to have high dislocation storage ability, with consequent increase in dislocation density and work hardening exponent, leading to decrease of YPE.

1. Introduction

Medium Mn steels continue to receive significant attention because of excellent mechanical properties and potential for automotive structural components. In the past decade, numerous studies have focused on obtaining large fraction of austenite with proper stability by optimizing chemical composition and adjusting heat treatment [1–4]. It was reported that ductility could be increased simultaneously with strength by transformation-induced plasticity (TRIP) mechanism, contributing to superior tensile property > 30 GPa·%, when austenite was present with ferrite or martensite in medium Mn steels. Especially, ultra-high strength (> 1.5 GPa) combined with high ductility (> 20%) were achieved in (austenite + martensite) duplex microstructure [5].

In order to achieve good strength-ductility balance, austenite should gradually transform over a wide range of strain [6]. It has been proven that Lüders bands directly results from the mechanical stability of austenite [7]. Austenite stability is known to depend on chemical composition [8], grain size [4,9], morphology [10], and crystallographic orientation of austenite [11], etc, among which chemical composition and grain size are the primary parameters [4,11]. Austenite stability can be varied by controlling the intercritical annealing (IA) temperature and the annealing time [2,12]. Moreover, Lüders bands were influenced by IA temperature in medium Mn steels [13,14].

The phenomenon of Lüders bands characterized by a stress plateau accompanied by serrations, which initiates at the onset of yielding and spreads for a certain strain, is referred as yield point elongation (YPE). The classical explanation for YPE phenomenon is static strain aging, which means that dislocations can be pinned by clusters of interstitial atoms, or Cottrell atmospheres [15]. A different mechanism that promotes Lüders band formation is ultra-fine grained (UFG) microstructure (grain size < 1 μm) [16]. With decreasing grain size, an increasing number of dislocations are trapped at grain boundaries and become immobile [17–19], which has a similar effect as the trapping of dislocations by interstitials. Medium-Mn steels commonly exhibit large YPE, some of them easily exceeding 10% [14,20,21]. It was reported that both low IA temperature and a globular microstructure supported the formation of large YPE. Moreover, it was recommended to provide a martensitic microstructure prior to intercritical annealing in order to limit YPE [20].

Although there are some studies on the YPE, the micromechanical origin of YPE is still unknown. The study described here concentrates on the influence of microstructural characteristics on YPE. A detailed characterization of microstructural evolution, including austenite (fraction, size, stability) and ferrite (size, texture) characteristics, and the resulting mechanical properties including YPE and work hardening behavior are presented.

2. Experimental

The experimental steel had a nominal composition (wt%) of Fe-

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Table 1
Chemical composition (wt%) of steel and critical temperatures (°C).

Mn	Al	C	Fe	Ac_1	Ac_3
11.20	1.95	0.22	Bal.	630	730

0.2C-11Mn-2Al, and the actual chemical composition is listed in Table 1. The ingot was heated at 1200 °C for 2 h, hot forged to rods with a section size of 100 mm × 30 mm, followed by air cooled to room temperature. Subsequently, the rods were soaked at 1200 °C for 2 h, hot rolled to 4 mm in thickness and finally air cooled to room temperature. The as-hot rolled sheets were then cold-rolled to 1 mm thickness.

In order to establish an appropriate heat treatment schedule, the critical temperatures Ac_1 and Ac_3 of the experimental steel were obtained by dilatometry and are listed in Table 1. For obtaining different microstructural constituents and grain size, the as-cold rolled sheets were annealed in the temperature range of 600–800 °C for 5 min, followed by water quenching. Additionally, to obtain similar austenite fraction but different austenite stability, the as-cold rolled sheets were annealed at 650 °C for different periods (2 min~48 h), followed by water quenching.

Tensile tests were conducted on specimens of 12.5 mm width and gauge length of 25 mm, using a universal testing machine (SANSCMT 5000) at a constant crosshead speed of 3 mm·min^{-1} at room temperature. The samples were etched with 25% sodium bisulfite aqueous solution. Microstructural examination was carried out using scanning electron microscope (SEM) equipped with electron backscatter diffraction (EBSD) and transmission electron microscope (TEM). The volume fraction of austenite was determined by X-ray diffraction (XRD) with CuKα radiation using direct comparison method [22], involving the use of integrated intensities of $(200)_\alpha$ and $(211)_\alpha$ peaks and those of $(200)_\gamma$, $(220)_\gamma$ and $(311)_\gamma$ peaks. The volume fraction of austenite V_A was calculated using equation [23]:

$$V_A = 1.4I_\gamma/(I_\alpha + 1.4I_\gamma) \quad (1)$$

where I_γ is the integrated intensity of austenite and I_α is the integrated intensity of phases with body-centered cubic structure.

3. Results and discussion

3.1. Microstructure and mechanical properties

SEM micrographs of cold-rolled sheets annealed at 600 °C, 650 °C, 700 °C,and 750 °C for 5 min, respectively, and then immediately quenched in water, are presented in Fig. 1. As shown in Fig. 1a, the microstructural constituents consisted of ferrite and austenite. The microstructure can be described into two types: strip-like and equiaxed / granular. The strip structure developed during cold rolling of partially recrystallized, evolved into equiaxed structure on annealing at 600 °C. For clarity, a mixture of austenite and ferrite strips are identified by a rectangle in Fig. 1a, and a high-magnification micrograph of this region is illustrated in Fig. 1e. It is distinct that austenite strips were present between the adjacent ferrite strips. As shown in Fig. 1b and c, the austenite and ferrite strips gradually developed into equiaxed microstructure with increase in annealing temperature. A small number of strip structure continue to be retained on annealing at 650 °C. However, it completely disappeared after annealing at 700 °C. When the samples were annealed at 750 °C, as shown in Fig. 1d, the microstructure comprised of martensite and austenite.

The measured austenite fraction as a function of annealing temperature or soaking time was summarized in Fig. 2. As illustrated in Fig. 2a, the austenite fraction increases from 55% to 89% in the temperature range of 600–700 °C, followed by drastic decrease to 46%, when quenching was carried out at 750 °C because of martensitic transformation, consistent with microstructure illustrated in Fig. 1d. Therefore, the austenite fraction is sensitive to annealing temperature. Furthermore, it is confirmed that the austenite fraction remains nearly constant when the samples were annealed at 650 °C for different periods (as evidenced in Fig. 2b).

Fig. 3 shows the engineering stress-strain plots of the annealed samples. As shown in Fig. 3a, it is noticed that YPE only appears in the sample annealed at 650 °C for 5 min (henceforth nominated as 650–5 min sample). Moreover, as demonstrated in Fig. 3b, it is clear that the length of YPE decreases with extended soaking time at 650 °C. To interpret this phenomenon, the interplay between microstructural characteristics and plastic deformation behavior including YPE and TRIP effect should be elucidated.

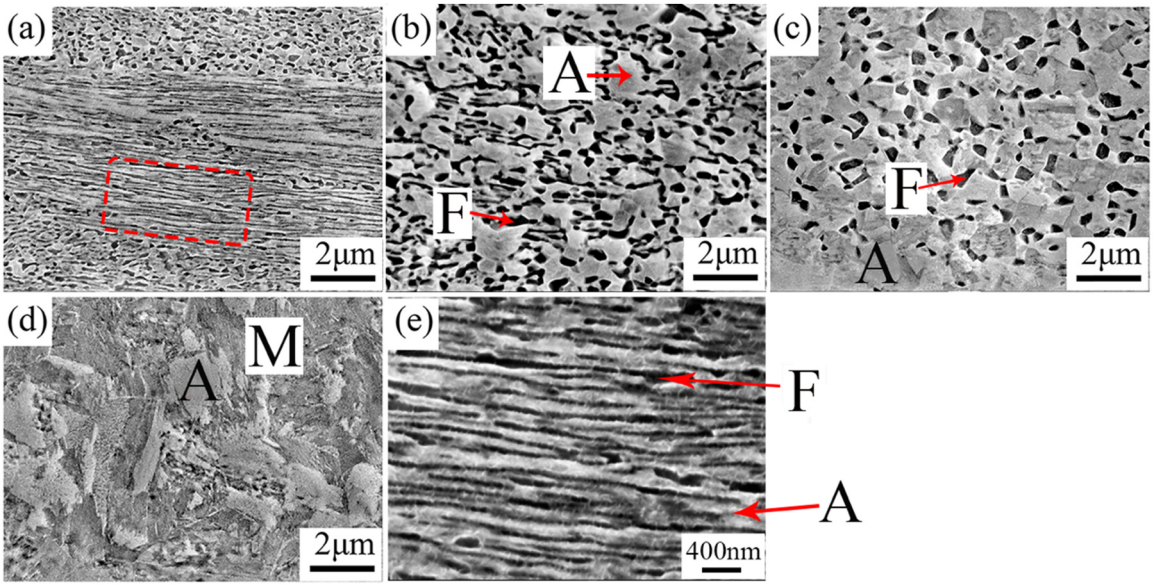

Fig. 1. SEM micrographs of the cold-rolled samples quenched from (a) 600 °C, (b) 650 °C, (c) 700 °C and (d) 750 °C, respectively and (e) high magnification of austenite and ferrite strips. The bright phase is austenite, and the dark one is ferrite. (A: austenite, F: ferrite, M: martensite).