Materials Science & Engineering A 676 (2016) 263–270

Contents lists available at ScienceDirect

Materials Science & Engineering A

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

Microstructure and deformation behavior of the hot-rolled medium manganese steels with varying aluminum-content

Z.H. Cai [a,*], B. Cai [a], H. Ding [a], Y. Chen [a], R.D.K. Misra [b,*]

[a] School of Materials Science and Engineering, Northeastern University, Shenyang 110819, China

[b] Laboratory for Excellence in Advanced Steel Research, Department of Metallurgical, Materials and Biomedical Engineering, University of Texas at El Paso, El Paso, TX 79968, USA

ARTICLE INFO

Article history:
Received 13 July 2016
Received in revised form
29 August 2016
Accepted 30 August 2016
Available online 31 August 2016

Keywords:
Austenite stability
δ-ferrite
TRIP effect
Work hardening
Tensile properties

ABSTRACT

We elucidate here the mechanistic contribution of the interplay between microstructural constituents and plastic deformation behavior in hot-rolled Fe-0.2C-11Mn-xAl steels containing 2–6 wt% Al. The decrease in austenite fraction with increase in Al-content was accompanied by decrease in tensile strength, while the δ-ferrite content and ductility increased. 2Al steel was characterized by ultrahigh ultimate tensile strength (UTS) of 1407 MPa, while 6Al steel exhibited extremely high total elongation (TE) of 65%. The superior ductility in 6Al steel is attributed to cumulative contribution of transformation induced plasticity (TRIP) effect and twinning induced plasticity (TWIP) effect. The increase in soft δ-ferrite phase with low microhardness led to increase in TE and decrease in UTS and work hardening rate.

1. Introduction

The reduction in the weight of car is a priority for automobile manufacturers. To achieve this goal, light metals such as aluminum and magnesium alloys are being considered in preference to steels. However, these alloys cannot be used to make certain structure parts, such as pillar and bumper. It is, therefore, a feasible approach to reduce the density of advanced high strength steels through the addition of light elements such as aluminum and magnesium. According to the rough estimates, every 1% addition of Al contributes to 1.25% decrease in steel density [1,2].

Low density steels can be categorized as ferrite-base [3], austenite-base [4,5], and duplex-base (ferrite+austenite) [6–8]. Ferritic low density steels generally have relatively high Al-content. It is reported that ferritic steels can have a maximum of 11 wt% of Al [3,9]. The addition of Al stabilizes α-ferrite, and facilitates the presence of δ-ferrite during solidification [10,11]. The addition of Mn and C compensates the effect of Al on phase stability and ensures austenite formation. Austenitic low density steels have high Mn-content and C-content.

Fe-Mn-C ternary alloy system with medium Mn-content (5–12%) and low C-content ($<0.2\%$) is potential candidate for automotive applications [12–14]. This class of steels exhibit high strength and good ductility combination, which is primarily derived from transformation-induced plasticity (TRIP) effect. To accomplish reduction in weight, recent studies focused on the addition of Al to medium-Mn TRIP steels. Moreover, excellent mechanical properties were obtained in Fe-Mn-C-Al alloy system. For example, Han et al. obtained tensile strength of 1095 MPa and total elongation of 42% in Fe-10Mn-0.14C-1.5Al (wt%) steel [15]. Suh et al. obtained tensile strength of 1000 MPa and ductility of 30% in Fe-6Mn-0.1C-3Al (wt%) steel [16]. Similarly, Park et al. demonstrated excellent combination of high tensile strength of 949 MPa and ductility of 54% in Fe-8Mn-0.23C-5.3Al [17].

It seems from the aforementioned studies and background that Al is a viable option in the development of low-density steels. However, the large addition of Al may introduce manufacturing difficulties during casting or hot rolling, which may be the result of precipitation of Fe_3Al intermetallic compounds [18]. Thus, an optimum Al content is required to optimize weight reduction and mechanical properties, and alleviate manufacturing difficulties. The objective of the study is aimed at elucidating the effect of Al-content on the microstructure, mechanical properties and deformation behavior in hot-rolled Fe-11Mn-0.2C-xAl steels.

2. Experimental

The nominal chemical composition of experimental steels (in wt%) was Fe-11Mn-0.2C-2Al (2Al steel), Fe-11Mn-0.2C-4Al (4Al steel) and Fe-11Mn-0.2C-6Al (6Al steel). The actual chemical

* 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.2016.08.119
0921-5093/

Table 1
Chemical composition (wt%) of three experimental steels.

	Mn	Al	C	Fe
2Al steel	11.20	1.95	0.22	Bal.
4Al steel	11.02	3.81	0.18	Bal.
6Al steel	10.75	6.08	0.21	Bal.

composition of the three experimental steels are listed in Table 1. The ingots were cast using a vacuum furnace and heated at 1200 °C for 2 h and hot forged to rods of section size ~100 mm × 30 mm, followed by air cooling to room temperature. Subsequently, the rods were soaked at 1200 °C for 2 h, and hot rolled to 4 mm thickness in the temperature range of 1150–850 °C, and finally air cooled to ambient temperature.

The experimental steels were subjected to quenching and tempering (Q&T) heat treatment, which was envisioned by us as an alternative and effective heat treatment [19–21]. First, they were annealed in the two-phase region or austenite region for 1 h, followed by water quenching. Second, the quenched samples were tempered at 200 °C for 20 min and air cooled to ambient temperature. Tempering was helpful in relieving the internal stress, but more importantly it improved the stability of austenite through the diffusion of C from δ-ferrite to austenite [21].

Tensile specimens with a width of 12.5 mm and a gauge length of 50 mm were machined from the heat-treated sheets with the tensile axis parallel to the prior rolling direction. Tensile tests were carried out at room temperature using a universal testing machine (SANSCMT5000) at a constant crosshead speed of 3 mm min^{-1}. The specification for the tensile specimen used was Chinese national standard GB/T 228—2002, which is equal to ISO 6892:1998. The samples were etched with 25% sodium bisulfite solution. Microstructural examination was carried out using optical microscope (OM), electron microprobe analysis (EMPA) and transmission electron microscope (TEM). Microhardness measurement was carried out by Vicker hardness tester. The selected pressure was 50 gf, and the holding time was 10 s. 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

3.1. Microstructure

SEM micrographs of as-hot-rolled steels are presented in Fig. 1. The microstructural constituents in 2Al steel consisted of martensite and austenite, while in 4Al steel besides martensite and austenite, δ-ferrite was also present. In 6Al steel, lamellar austenite was present between the adjacent δ-ferrite stripes. Fig. 2 illustrates the microstructure of hot rolled 2Al and 4Al steels heat treated at different temperatures, and Fig. 3 describes the microstructure of 6Al steel quenched at 650 °C, 850 °C, 950 °C and 1000 °C, respectively, followed by tempering at 200 °C. The microstructural constituents of the experimental steels as a function of quenching temperature are summarized in Table 2. The microstructural constituents in 2Al steel and 4Al steel varied with the quenching temperature, especially the austenite fraction, which was confirmed by XRD. In contrast to 2Al and 4Al steels, the microstructural constituents of 6Al steel consisted mainly of austenite and δ-ferrite stripes in the absence of martensite and α-ferrite.

The variation in the volume fraction of austenite obtained from XRD is summarized in Fig. 4. 2Al steel had a high austenite fraction of ~80% in the temperature range of 600–700 °C, followed by a dramatic decrease to ~25%, when quenching was carried out in the temperature range of 750–850 °C because of martensitic transformation, as evidenced in Fig. 2b. It is further estimated that ~55% martensite was developed during quenching. Similar trend in the austenite fraction was observed in 4Al steel. 4Al steel had lower austenite content (~70%) than 2Al steel. The austenite fraction in 4Al steel was deduced to ~10% when quenching in the range of 850–900 °C because of martensitic transformation (Fig. 2d). In contrast, the austenite fraction in 6Al steel was not strongly governed by the quenching temperature and was ~50% in the range of 650–1000 °C. Comparing the microstructure in Figs. 2 and 3, it is obvious that the fraction of δ-ferrite increased with increase in Al content, considering that Al is ferrite stabilizer. Moreover, as summarized in Table 2, there is no δ-ferrite in 2Al steel, and the fraction of δ-ferrite in 4Al steel estimated by Image-Pro Plus software was ~5%. The microstructural constituents in 6Al steel consisted of δ-ferrite and austenite, and it was confirmed by XRD results (Fig. 4) that the austenite fraction was ~50%, thus, the fraction of δ-ferrite was ~50%.

3.2. Mechanical properties

The mechanical properties of the three steels are summarized in Fig. 5. It may be seen that 6Al steel had the lowest ultimate tensile strength (UTS), but total elongation (TE) was the best among the three steels. In 6Al steel, there was only a small

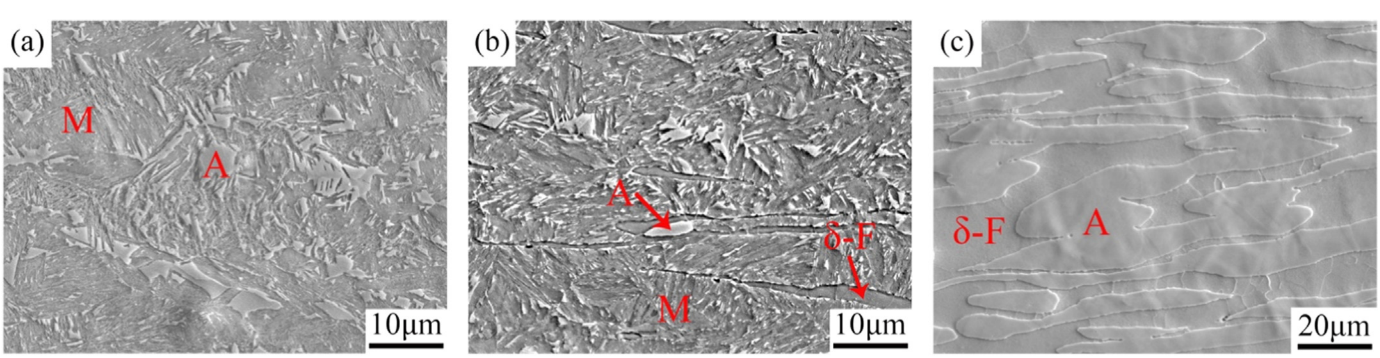

Fig. 1. SEM micrographs of three as-hot-rolled steels. (a) 2Al steel, (b) 4Al steel and (c) 6Al steel. (M: martensite, A: austenite, δ-F: δ-ferrite).