Materials Science & Engineering A 688 (2017) 237–243

Contents lists available at ScienceDirect

Materials Science & Engineering A

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

Warm ductility of 0.2% C–1.5% Si–5% Mn TRIP-aided steel

Koh-ichi Sugimoto[a,*], Hikaru Tanino[a], Junya Kobayashi[b]

[a] School of Science and Technology, Shinshu University, 4-17-1 Wakasato, Nagano 380-8553, Japan
[b] School of Science and Engineering, Ibaraki University, 4-12-1 Naka-narusawa, Hitachi 316-8511, Japan

A R T I C L E I N F O

Keywords:
Warm deformation
Tensile properties
Ductility
Medium Mn TRIP-aided steel
Retained austenite

A B S T R A C T

Warm tensile properties of 0.2% C–1.5% Si–5.0% Mn transformation-induced plasticity (TRIP)-aided steel sheets with annealed martensite matrix and retained austenite of 39.4 vol% were investigated for automotive applications. The product of tensile strength and total elongation (TS×TEl) of the TRIP-aided steel was enhanced to 50 GPa% by warm deformation at 150 and 200 °C which is significantly higher than that (30 GPa%) required for third generation advanced high-strength steels. The thermal stability of the retained austenite was low, because the low stacking fault energy promotes the ε-martensitic transformation. The mechanical stability of the retained austenite, however, increased with an increase in the deformation temperature of the steel, because the ε-martensitic and the strain-induced α′-martensitic transformations were suppressed with increasing deformation temperature. Therefore, the high value of the TS × TEl of the steel subjected to warm deformation is principally associated with the high volume fraction of the retained austenite and its optimum metastability which maximizes the TRIP effect.

1. Introduction

The twinning-induced plasticity (TWIP) [1] and the transformation-induced plasticity (TRIP) [2] of either austenite or metastable retained austenite in steels significantly improve the ductility and the formability of the steels. Considering this fact, second-generation advanced high-strength steels (AHSSs) such as high Mn TWIP/TRIP steels [1,3,4], and third-generation AHSSs such as medium Mn TRIP-aided steels with annealed martensite [4–15] and martensite matrices [4,16–18], TRIP-aided bainitic ferrite (TBF) steels [19–22], TRIP-aided martensitic (TM) steels [23–26], quenching and partitioning (Q & P) steels [27–29], and maraging TRIP steels [30,31] have been developed, with the aim of reducing the weights of automobiles and improving their crashworthiness.

Generally, Mn promotes austenite formation and thus increases the volume fraction of retained austenite in steels as an austenite stabilizer [5,6]. Medium Mn TRIP-aided steels with annealed martensite matrix exhibit high values of the product of tensile strength and total elongation (TS × TEl) [4–15] due to the TRIP effect of a large amount of retained austenite. Sugimoto et al. have reported that warm deformation stabilizes the retained austenite and enhances the ductility of 0.4% C–1.5% Si–1.5% Mn [32] and 0.2% C– (1.0–2.0)% Si– (1.0–2.5)% Mn [33] TRIP-aided steels with polygonal ferrite matrix (TPF steels). Chen et al. [11] and Rana et al. [12] have also reported the effects of warm deformation on the tensile properties of medium Mn TRIP-aided steels such as 0.2% C–4.74% Mn and 0.14% C–0.21% Si–1.55% Al–7.4% Mn steels, respectively. However, the warm tensile properties of medium Mn TRIP-aided steel containing 1.5% Si, and the relationship between the TS × TEl and retained austenite characteristics have not been investigated so far.

In the current study, the warm tensile properties of 0.2% C–1.5% Si–5.0% Mn TRIP-aided steel with annealed martensite matrix were investigated. Additionally, the relationship between the warm tensile properties and the retained austenite characteristics was determined by studying the thermal and the mechanical stabilities of retained austenite.

2. Experimental procedure

100 kg ingot of 0.2% C–1.5% Si–5% Mn steel (5% Mn steel) were prepared by vacuum melting. The ingot was hot forged to 50 mm square and rough hot rolled into 30 mm in thickness, followed by finish hot rolling to 3 mm. The reheating temperature and finishing rolling temperature were 1200 °C and 850 °C, respectively. Successively, the plates were cold-rolled into 1.2 mm-thick sheets, assisted with annealing at 650 °C. Samples of 0.2% C–1.5% Si–1.5% Mn steel (1.5% Mn steel) were also prepared by a similar process for comparison. The chemical compositions of the steel sheets are listed in Table 1. The austenitic and the ferritic transformation temperatures (Ae_3 and Ae_1, respectively; °C) and the martensite-start and -finish temperatures (M_s

* Corresponding author.
E-mail address: sugimot@shinshu-u.ac.jp (K.-i. Sugimoto).

http://dx.doi.org/10.1016/j.msea.2017.02.018
Received 28 November 2016; Received in revised form 3 February 2017; Accepted 4 February 2017
Available online 06 February 2017
0921-5093/

Table 1
Chemical composition [mass%] and transformation temperatures [°C] of 1.5% and 5% Mn steels.

Steel	C	Si	Mn	P	S	Al	N	O	Ae_3	Ae_1	M_S	M_f
1.5% Mn	0.20	1.49	1.50	0.006	0.0015	0.035	0.0038	< 0.001	847	719	420	300
5% Mn	0.21	1.50	4.94	0.005	0.0016	0.032	0.0020	< 0.001	741	657	282	150

and M_f, respectively; °C) of the steels were determined using a dilatometer.

The microstructures of the steels were examined by transmission electron microscopy (TEM; JEM-2010, JEOL Ltd., Tokyo) and electron backscatter diffraction pattern analysis using field-emission scanning electron microscopy (SEM; JSM-6500F, JEOL Ltd., Tokyo).

The volume fraction of retained austenite was quantified by X-ray diffraction (XRD; RINT2000, Rigaku Co., Tokyo) using Mo-Kα radiation [19–21]. The carbon concentration ($C\gamma$; mass%) of the specimens was estimated by substituting a lattice constant of austenite measured by XRD into the empirical equation proposed by Dyson and Holmes [34].

The thermal stability of the retained austenite was evaluated using the fraction of retained austenite transformed on cooling or heating to the ambient temperature. In this case, the holding time for cooling was 1200 s. The mechanical stability of the retained austenite is defined by the "strain induced transformation factor, k" obtained using the equation [21–26],

$$\ln f\gamma = \ln f\gamma_0 - k\varepsilon \quad (1)$$

where, $f\gamma_0$ is the initial volume fraction of retained austenite and $f\gamma$ is the volume fraction of retained austenite after being subjected to the true plastic strain, ε.

The tensile specimens with gauge length of 50 mm, gauge width of 12.5 mm, and thickness of 1.2 mm were machined from the cold-rolled steel sheets. Subsequently, the specimens were subjected to the heat treatment shown in Fig. 1, namely, quenching in oil after heating to $T_\gamma = Ae_3 + 50$ °C for 1200 s, intercritical annealing at $T_{\alpha+\gamma} = 780$ and 680 °C between Ae_1 and Ae_3 for 1200 s, followed by isothermal transformation (IT) at $T_{IT} = M_S - 100$ °C for $t_{IT} = 500$ or 5000 s for the 1.5 and the 5% Mn steels, respectively. The intercritical annealing temperatures correspond to the temperatures when the volume fractions of both ferrite (annealed martensite in this heating process) and austenite are 50%. In the IT process, the holding times (t_{IT}s) that ensure optimum impact toughness [15] were adopted.

The tensile tests were carried out using an Instron tensile testing machine (AD-10TD, Shimadzu Co., Kyoto) in the temperature range of −70–300 °C and at a mean strain rate of 2.8×10^{-3} s^{-1} (crosshead speed: 10 mm/min). Each specimen was directly cooled using dry ice, ethyl alcohol, and liquid nitrogen, and heated using a pair of plate heaters (70×90 mm^2) during the tensile test.

steel	T_γ [°C]	$T_{\alpha+\gamma}$ [°C]	T_{IT} [°C]	t_{IT} [s]
1.5% Mn	900	780	320	500
5% Mn	800	680	180	5000

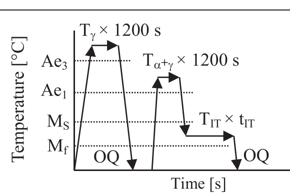

Fig. 1. Heat-treatment profile for the 1.5% and the 5% Mn steels. OQ refers to quenching in oil.

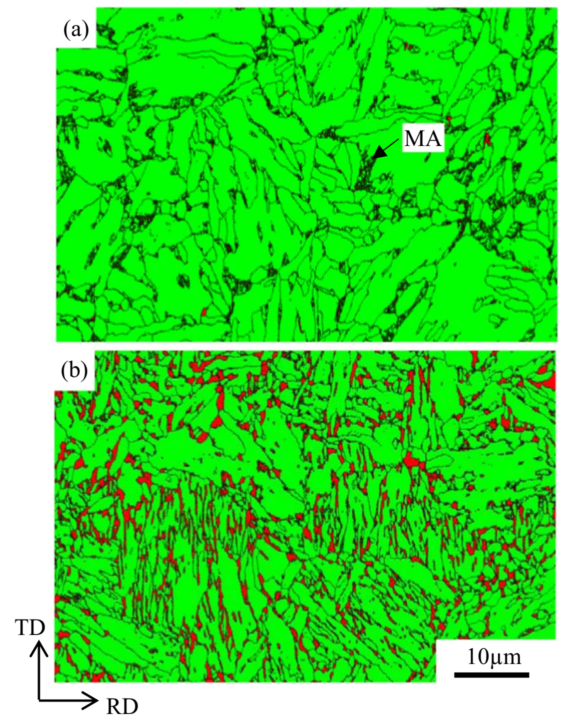

Fig. 2. Phase maps of the heat-treated (a) 1.5% and (b) 5% Mn steels, in which yellowish green, red, and gray regions denote annealed martensite matrix, retained austenite and α′-martensite-austenite (MA) phases, respectively. The terms, TD and RD denote the thickness and the rolling directions, respectively.

3. Results

3.1. Microstructure

Fig. 2 shows the microstructures of the heat-treated 1.5% and 5% Mn steels. Table 2 shows the retained austenite characteristics of both the steels. In these steels, the microstructure consists of an annealed martensite matrix and retained austenite islands, although the 1.5% Mn steel contains a small amount of the α′-martensite-austenite (MA) phase. The 5% Mn steel exhibited smaller lath size of annealed martensite, and larger size and higher volume fraction (39.4 vol%) of retained austenite than the 1.5% Mn steel. According to Tanino et al. [15], the retained austenite in 5% Mn steel is enriched with Mn to around 8 mass%, although the C concentration ($C\gamma_0$) is decreased (Table 2).

Fig. 3 shows the TEM image of the heat-treated 5% Mn steel. Similar to the 1.5% Mn steel [20], the dislocation density in the annealed martensite of 5% Mn steel is very low. Furthermore, annealing twins were not observed in the retained austenite of the 5% Mn steel. Therefore, the matrices of the 1.5 and the 5% Mn steels differ only in the lath size and the concentrations of Mn and C.

3.2. Tensile properties

The engineering stress-strain curves of the 1.5% and the 5% Mn steels deformed at temperatures in the range of −70–300 °C are shown in Fig. 4. The tensile properties of the corresponding steels are shown