Archives of Materials Science and Engineering
Volume 80
Issue 1
July 2016
Pages 5-15
International Scientific Journal published monthly by the World Academy of Materials and Manufacturing Engineering

Warm stretch-formability of 0.2%C-1.5%Si-(1.5-5.0)%Mn TRIP-aided steels

K. Sugimoto [a,*], H. Tanino [a], J. Kobayashi [b]
[a] Graduate School of Science and Technology, Shinshu University,
4-17-1 Wakasato, Nagano 380-8553, Japan
[b] Graduate School of Science and Engineering, Ibaraki University,
4-12-1 Naka-narusawa, Hitachi 316-8511, Japan
* Corresponding e-mail address: sugimot@shinshu-u.ac.jp

ABSTRACT

Purpose: Warm stretch-formability of 0.2%C-1.5%Si-(1.5-5.0)%Mn transformation-induced plasticity (TRIP)-aided sheet steels with annealed martensite matrix was investigated for automotive applications. Additionally, the warm stretch-formability was related with the retained austenite characteristics.

Design/methodology/approach: This study was aimed to enhance the stretch-formability by warm forming which stabilizes mechanically a large amount of metastable retained austenite in the steels.

Findings: The warm stretch-formability increased with an increase in Mn content. The stretch-formability of 5% Mn steel was improved by warm forming at peak temperatures of 150-300°C, which was the same level as that of 0.2%C-1.5%Si-1.5%Mn0.05%Nb TRIP-aided martensitic steel. The superior warm stretch-formability was caused by a large amount of mechanically stabilized retained austenite which suppresses considerably void initiation and growth at interface between matrix and transformed martensite. Higher peak temperatures for the stretch-formability than that for the total elongation was associated with high mean normal stress on stretch-forming.

Research limitations/implications: The effect of warm forming on the stretch-formability is smaller than that on the ductility.

Practical implications: Investigation results can be easily applied to industrial technology.

Originality/value: This paper presents an important result which the stretch-formability of 5% Mn TRIP-aided steel is mainly improved by stabilizing of retained austenite with low stacking fault energy. On the forming, only strain-induced α'-martensite transformation takes place and suppresses the void growth. The strain-induced bainite transformation never occurs during forming in 5% Mn steel, differing from conventional 1.5% Mn TRIP-aided steel.

Keywords: Medium Mn TRIP-aided steel; Stretch-formability; Warm forming; Retained austenite; Mechanical stability; Strain-induced martensite transformation

Reference to this paper should be given in the following way:

K. Sugimoto, H. Tanino, J. Kobayashi, Warm stretch-formability of 0.2%C-1.5%Si-(1.5-5.0)%Mn TRIP-aided steels, Archives of Materials Science and Engineering 80/1 (2016) 5-15.

MATERIALS

1. Introduction

It is well known that the transformation-induced plasticity (TRIP) [1] of metastable retained austenite improves the product of tensile strength and total elongation (TS×TEl) of first-generation advanced high-strength steels (AHSSs), such as low-alloy TRIP-aided steels with polygonal ferrite matrix (TPF steel) [2-8]. Recently, to improve further TS×TEl, third-generation AHSSs, such as TRIP-aided bainitic ferrite (TBF) steels [9-13], TRIP-aided martensitic (TM) steels [14-8], quenching and partitioning steels with a mixed bainite/martensite matrix [19,20], and medium-Mn TRIP-aided steels with annealed martensite [21-31] and martensite matrix [32-34], have been developed with the aim of reducing the weight and improving the crash safety of automobiles. A target of TS×TEl in these third-generation AHSSs is greater than 30 GPa%, which is lower than that (higher than 50 GPa%) of second-generation AHSSs, such as twinning-induced plasticity steels [26,35].

According to Sugimoto et al. [36], TS×TEl of 0.2%C-1.5%Si-5%Mn TRIP-aided steel with annealed martensite matrix is considerably improved by warm deformation at 150 to 200°C, because a large amount of retained austenite is considerably stabilized on warm forming, in the same way as for 0.2%C-(1.0-2.5)%Si-(1.0-2.0)%Mn TPF steels [37-39]. Additionally, Chen et al. [28] and Rana et al. [29] reported that warm deformation improves the ductility of medium-Mn TRIP-aided steels. However, there has been no study of warm formability of medium-Mn TRIP-aided steel with annealed martensite matrix.

The present paper investigates the warm stretch-formability of 0.2%C-1.5%Si-(1.5-5)%Mn TRIP-aided sheet steels with annealed martensite matrix for automotive applications. Additionally, the relationship between these stretch-formabilities and the retained austenite characteristics is discussed.

2. Experimental procedure

Three types of steels with varying Mn contents (1.5, 3, and 5% Mn steels) were prepared as 100 kg slabs via vacuum melting. These slabs were then heated to 1200°C and hot-rolled at 850°C to a thickness of 5 mm. Next, the plates were cold-rolled into 1.2-mm-thick sheets. Steels containing 3% and 5% Mn were annealed at 650°C to aid in cold-rolling. The chemical compositions of the steel sheets are listed in Table 1. The austenitic and ferritic transformation temperatures (Ae_3 and Ae_1, respectively; °C) and the martensite start and finish temperatures (M_s and M_f, respectively; °C) of the steels were determined using a dilatometer.

Table 1.
Chemical composition (mass%) and transformation temperatures (°C) of 1.5, 3 and 5% Mn steels

steel	C	Si	Mn	P	S	Al
1.5%Mn	0.20	1.49	1.50	0.006	0.0015	0.035
3%Mn	0.20	1.52	2.98	0.006	0.0016	0.037
5%Mn	0.21	1.50	4.94	0.005	0.0016	0.032

steel	N	O	Ae_3	Ae_1	M_S	M_f
1.5%Mn	0.0038	<0.001	847	719	420	300
3%Mn	0.0034	<0.001	797	689	363	220
5%Mn	0.0020	<0.001	741	657	282	150

steel	T_γ, °C	$T_{\alpha+\gamma}$, °C	T_{IT}, °C	t_{IT}, s
1.5%Mn	900	780	320	500
3% Mn	850	720	260	1000
5% Mn	800	680	180	5000

Tensile specimens with gauge length of 50 mm and width of 12.5 mm parallel to the rolling direction, and stretch-forming specimens of dimension of 50 mm square were machined from the cold-rolled sheet steels. These specimens were subjected to the heat treatment shown in Figure 1, specifically quenching in oil after heating to $T_\gamma = Ae_3$+50°C for 1200 s, and then intercritical annealing at $T_{\alpha+\gamma}$ = 780, 720, and 680°C between Ae_1 and Ae_3 for 1200 s for 1.5, 3, and 5% Mn steels respectively, followed by isothermal transformation (IT) at $T_{IT} = M_S$-100°C for t_{IT} = 500-5000 s. The intercritical temperatures were determined as the temperatures at which the volume fractions of ferrite and austenite were both 50%. Holding times for optimum ductility [31] were adopted to determine t_{IT}s.

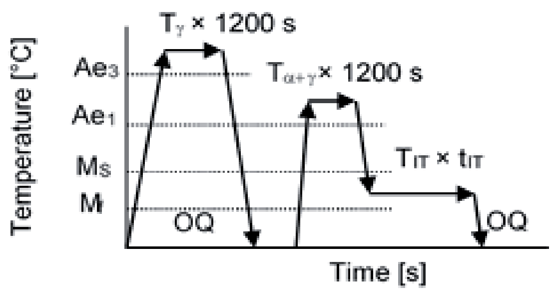

Fig. 1. Heat treatment profile for 1.5, 3, and 5% Mn steels. OQ: quenching in oil

The microstructure of the steel was examined via 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 via X-ray diffractometry using Mo-Kα radiation (XRD; RINT2000, Rigaku Co., Tokyo) [16,17]. The carbon concentration ($C\gamma$; mass%) of the retained austenite was estimated by substituting the austenite lattice constant measured via XRD into the empirical equation proposed by Dyson and Holmes [40].

The mechanical stability of the retained austenite was defined using the "strain-induced transformation factor k" in the following equation [4-7,16,17]:

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

where $f\gamma_0$ and $f\gamma$ are the volume fractions of retained austenite before and after straining to the true plastic strain (ε) via tension, respectively.

Tensile tests were carried out on an Instron-style tensile testing machine (AD-10TD, Shimadzu Co., Kyoto), over a temperature range of 25 to 300°C, and at a mean strain rate of 2.8×10^{-3} s^{-1} (crosshead speed: 10 mm/min). Each specimen was directly heated using a pair of plate heaters (70×90 mm^2) during the tension tests.

Stretch forming tests were performed using the same testing machine used in the tensile tests to measure the maximum stretch-forming load (P_{max}) and the maximum stretch height (H_{max}). The forming temperatures were between 25 and 300°C and the load speed was 1 mm/min. Test pieces were set on stretch forming dies with a circular bead and were then heated in a circular furnace (Fig. 2). A punch tool with a curvature radius of 8.7 mm and a graphite lubricant were employed for the stretch forming [4,16,17].

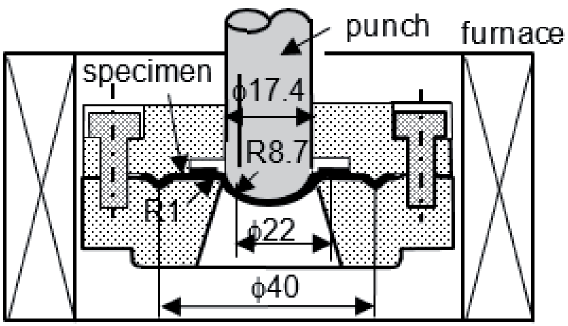

Fig. 2. Dies and circular furnace for stretch forming

3. Results

3.1. Microstructure and retained austenite characteristics

Figure 3 shows the microstructures of 1.5, 3 and 5% Mn steels. Table 2 shows their retained austenite characteristics. The microstructures of the steels consist of annealed martensite matrix and retained austenite islands, although 1.5% Mn steel contains a small amount of α'-martensite-austenite (MA) mixed phase. As the Mn content of the steels increases, the lath size of the annealed martensite decreases and the volume fraction and size of the retained austenite increase. According to Sugimoto et al. [33], the Mn concentration of retained austenite in 5% Mn steel is around 1.5 times the overall Mn content (around 8 mass%), although the C concentration decreases.

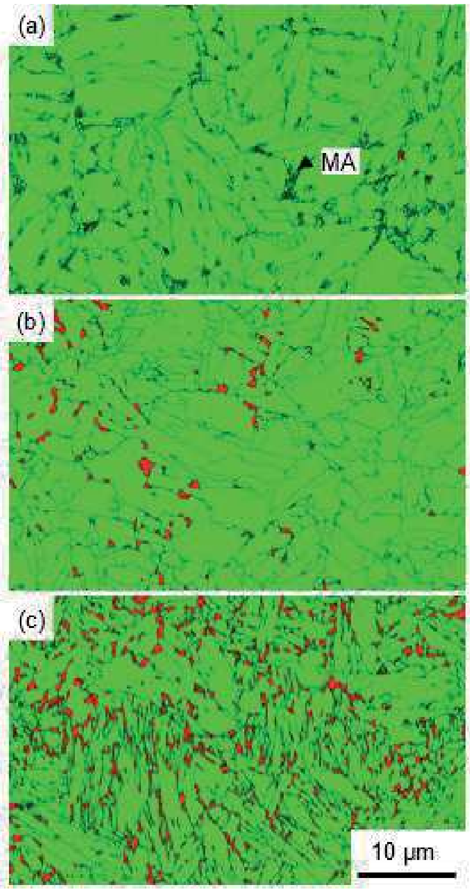

Fig. 3. Phase maps of (a) 1.5, (b) 3 and (c) 5% Mn steels, in which yellowish green and red phases denote annealed martenite matrix and retained austenite, respectively. MA: α'-martensite-austenite mixed phase

Table 2.
Retained austenite, tensile and stretch-forming properties of 1.5, 3 and 5% Mn steels

steel	T_F	$f\gamma_0$	$C\gamma_0$	YS	TS	UEl	TEl
1.5% Mn	25	12.0	0.71	407	873	20.0	24.1
	100			430	789	18.2	21.2
	150			511	817	16.4	20.8
	200			522	849	19.2	23.3
	250			491	857	12.7	16.2
	300			524	893	13.1	15.4
3% Mn	25	23.8	0.54	549	897	15.9	19.6
	100			529	852	30.6	34.3
	150			547	804	37.7	43.8
	200			501	829	19.0	22.2
	250			477	932	13.5	17.4
	300			376	1077	16.7	19.0
5% Mn	25	39.4	0.32	686	1168	29.4	30.5
	100			650	938	36.6	41.5
	150			691	984	46.5	50.2
	200			635	962	49.6	52.8
	250			626	963	35.2	41.5
	300			606	915	23.2	29.8

steel	T_F	TS×TEl	TS_{25}× TEl	P_{max}	H_{max}	TS_{25}×H_{max}
1.5% Mn	25	21.0	21.0	35.3	9.4	8.2
	100	16.7	18.5	36.1	9.8	8.6
	150	17.0	18.2	35.4	9.7	8.4
	200	19.8	20.3	37.9	9.7	8.4
	250	13.9	14.1	37.7	9.7	8.4
	300	13.8	13.4	41.2	9.4	8.2
3% Mn	25	17.6	17.6	40.9	9.5	8.5
	100	29.2	30.8	41.0	9.9	8.9
	150	35.2	39.2	34.8	10.2	9.1
	200	27.5	19.9	34.3	10.0	9.0
	250	16.2	15.6	34.2	9.8	8.8
	300	20.4	17.0	39.3	9.8	8.8
5% Mn	25	35.6	35.6	48.9	9.4	11.0
	100	38.9	48.4	44.4	10.1	11.8
	150	49.4	58.6	41.2	10.2	11.9
	200	50.8	61.7	41.1	10.5	12.3
	250	40.0	48.4	41.7	10.1	11.8
	300	27.3	34.8	45.1	10.3	12.0

Figure 4 shows a TEM image of heat-treated 5% Mn steel. Similar to 1.5 and 3% Mn steels, the dislocation density of the annealed martensite is very low and no carbide prcipitates. The matrix structures of 1.5, 3 and 5% Mn steels are thought to differ in lath size, and Mn and C concentrations.

Figure 5(a) shows the effect of Mn content on the original volume fraction of retained austenite. The original retained austenite fraction increases with the Mn content.

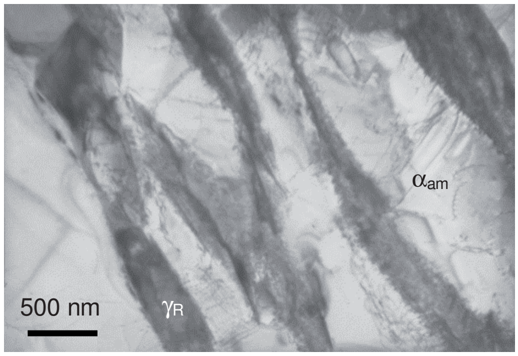

Fig. 4. TEM image of as-heat-treated 5% Mn steel, in which α_{am} and γ_R represent annealed martensite and retained austenite, respectively

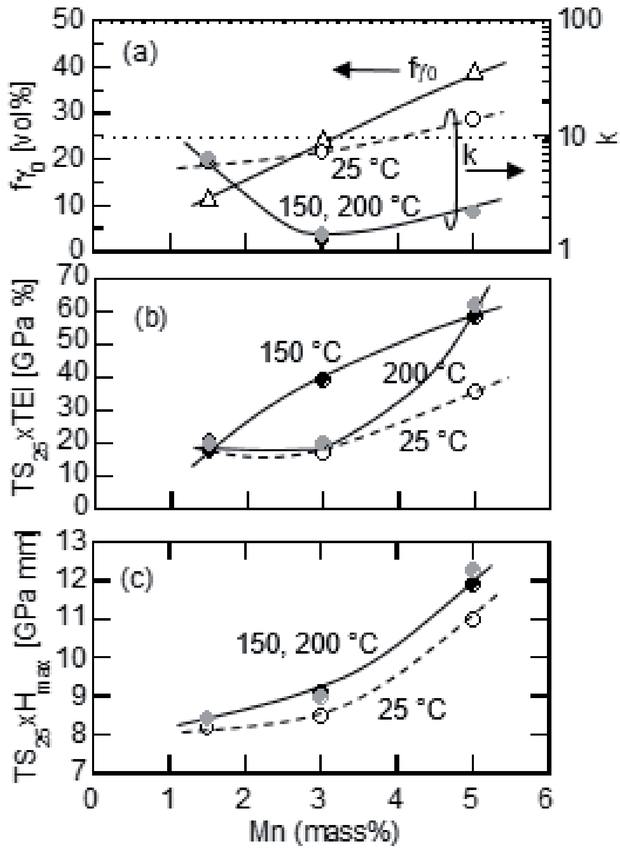

Fig. 5. Variations in (a) volume fraction ($f\gamma_0$) and k value of retained austenite, (b) product of TS at 25°C and TEl at ambient forming temperature (TS_{25}×TEl), and (c) product of TS at 25°C and H_{max} at ambient forming temperature (TS_{25}×H_{max}) as a function of Mn content in steels formed at T_F = 25 (○, △), 150 (●) and 200°C (●)

Figure 6 shows the variations in the k value as a function of forming temperature in the corresponding steels. The k value of 3% Mn steel reaches its minimum at T_S = 150 and 200°C, although the k value of 1.5% Mn steel is only weakly dependent on the forming temperature. On the other hand, the k value of 5% Mn steel decreases as the forming temperature increases, in contrast to the behaviors of 1.5 and 3% Mn steels. At 25°C, 3 and 5% Mn steels possess higher k values than 1.5% Mn steel. At 200°C, the k values of 3 and 5% Mn steels are much lower than that of 1.5% Mn steel. In this case, the k value of 3% Mn steel is lower than that of 5% Mn steel. Mn content dependences of the k values at 25, 150 and 200°C of the steels are shown in Figure 5(a).

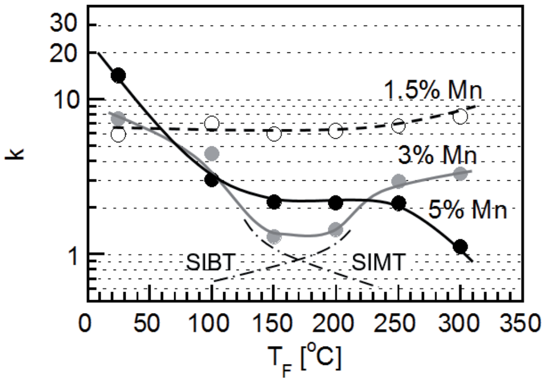

Fig. 6. Variations in k value as a function of forming temperature (T_F) in 1.5, 3 and 5% Mn steels. "SIMT" and "SIBT" mean strain-induced α'-martensite and bainite transformations, respectively

According to Sugimoto et al. [36], the strain-induced α'-martensite transformation (SIMT) occurs via ε-martensite in 5% Mn steel because the retained austenite possesses a low stacking fault energy [41]. In addition, the strain-induced bainite transformation (SIBT) [38,39] is suppressed in 5% Mn steel, but not in 1.5 and 3% Mn steels [36]. Thus, the low k values of 5% Mn steel at 150 to 300°C are thought to result from the suppression of SIMT and the absence of SIBT. On the other hand, the minimum k value for 3% Mn steel may appear because both SIBT and SIMT are suppressed.

3.2. Tensile properties

The engineering stress-strain curves of 1.5, 3 and 5% Mn steels deformed at 25 to 300°C are shown in Figure 7. The tensile properties of 3 and 5% Mn steels exhibit significant dependence on forming temperature. When the deformation temperatures are between 100 and 200°C, frequent serrations occur on the flow curves and the flow stress in 3 and 5% Mn steels decreases. A yield plateau appears in this temperature range, especially in 5% Mn steel. Unremarkable serrations occur at 100 to 300°C in 1.5% Mn steel.

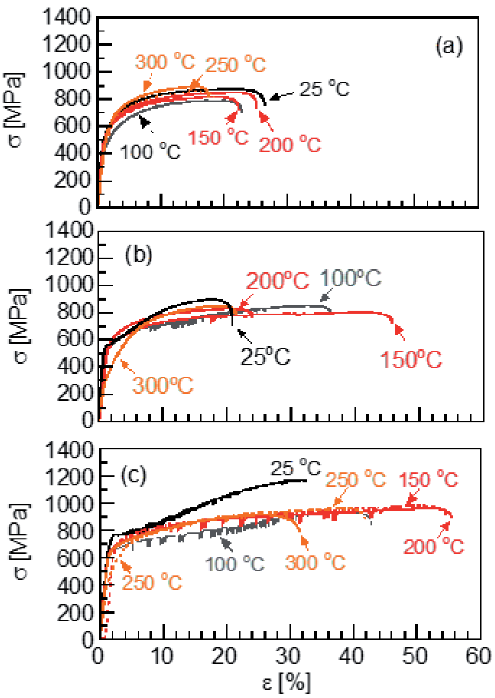

Fig. 7. Engineering stress-strain curves at 25 to 300°C in (a) 1.5, (b) 3 and (c) 5% Mn steels

The tensile properties of the corresponding steels are shown in Table 2. Warm deformation decreases the tensile strengths, although they are increased at 200-300°C, except in 5% Mn steel. As a result, the tensile strengths of 1.5 and 3% Mn steels reach their minima at 100-150°C. The total elongations of the 1.5, 3 and 5% Mn steels exhibit maximum values at peak temperatures T_Ps of 25, 150 and 150-200°C respectively, however there is indistinct deformation temperature dependence in 1.5% Mn steel. For the 3% Mn steel, T_P agrees well with temperature T_S corresponding to the minimum k value (Fig. 6). The highest TS and largest TEl are obtained with 5% Mn steel.

The largest TS×TEl of 5% Mn steel is over 50 GPa%, which comfortably exceeds the 30 GPa% target for third-generation AHSSs. The maximum TS×TEl evaluated using TS at 25°C (TS_{25}×TEl) exceeds 60 GPa%. As shown in

Figure 5(b), TS_{25}×TEl increases with the Mn content in steels formed at 150°C. Sugimoto et al. [36], reported that this is caused by the TRIP effect due to a large amount of retained austenite and its mechanical stabilization.

3.3. Stretch formability

Figure 8 shows samples of 1.5, 3 and 5% Mn steels formed at 25 and 200°C. Figure 9 shows the forming temperature dependences of P_{max}, H_{max} and the product of TS at 25°C and H_{max} (TS_{25}×H_{max}) of the corresponding steels. H_{max} and TS_{25}×H_{max} of the 5% Mn steel were increased by warm forming at peak temperatures T_P^* = 150-300°C, while P_{max} was low at 150-250°C. In contract, T_P^*s of 1.5 and 3% Mn steels were both 100-200°C. As shown in Figure 5(c), TS_{25}×H_{max} at 150 and 200°C increases with an increase in Mn content, in the same way as at 25°C.

Fig. 10(b) shows the H_{max}-TS_{25} relation of several steels. Warm TS_{25}×H_{max} of the 5% Mn steel is higher than those of 0.2%C-1.5%Si-1.5%Mn-0.05%Nb TBF and 0.082%C-0.88%Si-2.0%Mn ferrite-martensite dual-phase (DP) steels, and at the same level as that of 0.2%C-1.50%Si-1.5%Mn-0%Cr-0.05%Nb TM steel [16,17]. It is noteworthy that TS_{25}×TEl of 5% Mn steel is six times higher than that of the TM steel (Fig. 10(a)).

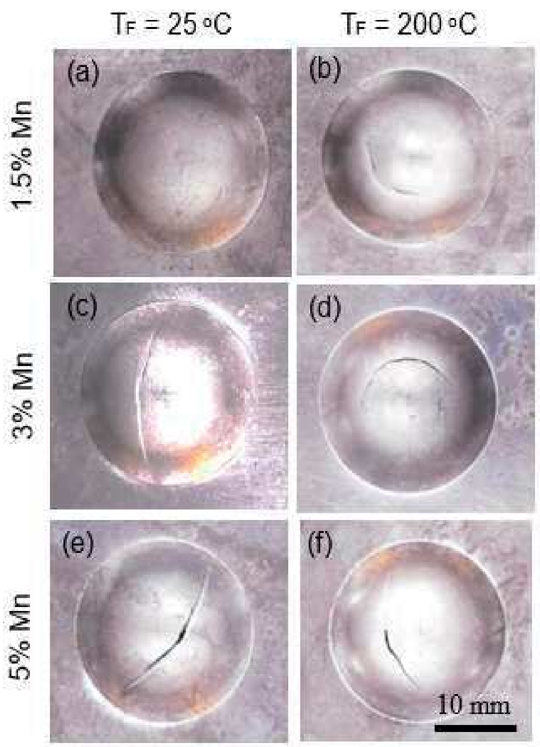

Fig. 8. Samples of 1.5, 3 and 5% Mn steels formed at 25 and 200°C

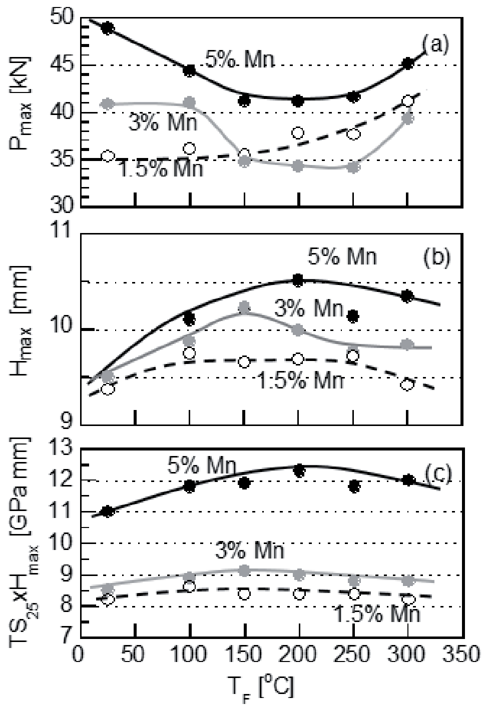

Fig. 9. Variations in (a) maximum forming load on cracking (P_{max}), (b) maximum stretch height (H_{max}) and (c) combination of TS at 25°C and H_{max} at ambient temperature (TS_{25}×H_{max}) as a function of forming temperature (T_F) in 1.5 (○), 3 (●) and 5% (●) Mn steels

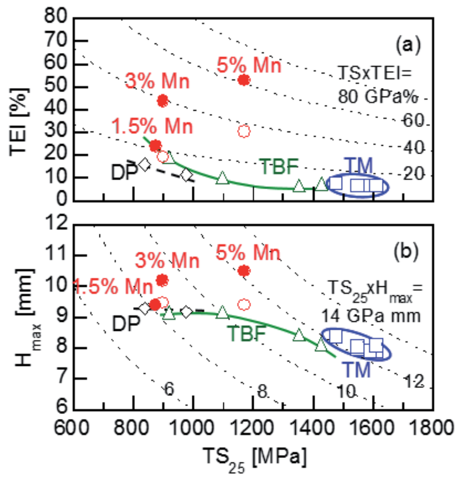

Fig. 10. (a) Tel-TS_{25} and (b) H_{max}-TS_{25} relations of 1.5, 3 and 5% Mn steels (●) formed at 25 (○) and 150°C (●), respectively. TM (□): 0.2%C-1.50%Si-1.5%Mn-0.05%Nb TRIP-aided martensitic steel, TBF (△): 0.2%C-1.5%Si-1.5%Mn-0.05%Nb TRIP-aided bainitic ferrite steel austempered at 300-450°C, DP (◇): 0.082%C-0.88%Si-2.0%Mn ferrite-martensite dual-phase steel

Fig. 11 shows the true thickness strain distribution of 1.5, 3 and 5% Mn steel samples after stretch forming at 25, 200, and 300°C. It is found that the thickness strain of 5% Mn steel is considerably increased by warm forming at 200°C. Additionally, the difference between the thickness strain ($\Delta\varepsilon_t$: see Fig. 11(c)) at the center and the maximum thickness strain is smaller than that of 1.5% Mn steel. For 1.5% Mn steel, a higher thickness strain is obtained by forming at 25°C, although H_{max} obtained by forming at 25 °C is lower than that obtained by forming at 200°C. 3% Mn steel exhibits tendency between 1.5 and 5% Mn steels.

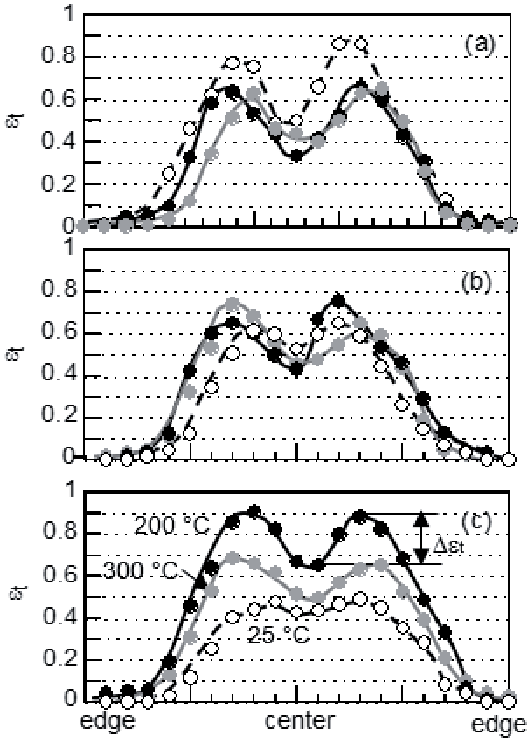

Fig. 11. Distributions of true thickness strain (ε_t) of (a) 1.5, (b) 3 and (c) 5% Mn steel samples after stretch-forming at (a) 25 (○), (b) 200 (●) and (c) 300°C (●)

Figure 12 shows SEM images of fractured region of 1.5, 3 and 5% Mn steels after stretch-forming at 25 and 200°C. When theses steels were formed at 200°C, void initiation and growth are suppressed considerably, similar to case in uniaxial tension, especially in 5% Mn steel.

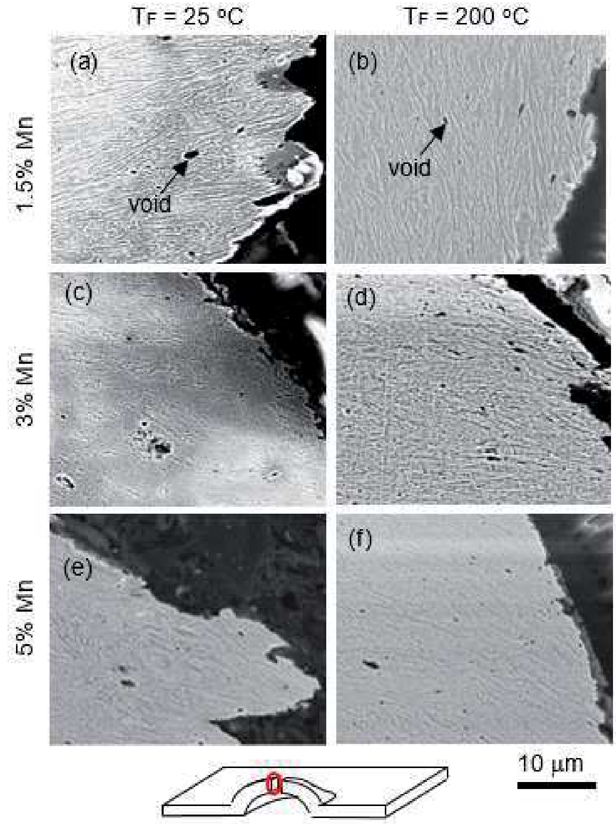

Fig. 12. SEM images of fracture regions of 1.5, 3 and 5% Mn steel specimens after stretch-forming at 25 and 200°C. (a): ε_t = 0.65, (b): ε_t = 0.66, (c): ε_t = 0.53, (d): ε_t = 0.60, (e): ε_t = 0.44, (f): ε_t = 0.86

4. Discussion

4.1. High warm stretch-formability of 5% Mn steel

In general, the stretch-formability of TRIP-aided steel relating to UEl and TEl is controlled by the retained austenite characteristics such as the original volume fraction and mechanical stability of the retained austenite [4,38], the second-phase morphology [4], and matrix structure [4]. In this case, mechanically stablized retained austenite enhances the stretch-formability of the steel because the volume expansion on the SIMT relaxes plastically the localized stress concentration. Fig. 13(b) plots the $TS_{25}\times H_{max}$-k relation for 1.5, 3 and 5% Mn steels. Warm $TS_{25}\times H_{max}$ of 5% Mn steel is higher than those of 1.5 and 3% Mn steels, although $TS_{25}\times H_{max}$ increases with decreasing k. Such a tendency resembles the relationship between $TS_{25}\times TEl$ and k (Fig. 13(a)), although the difference in $TS_{25}\times H_{max}$s between 1.5% and 5% Mn steels ($\Delta TS_{25}\times H_{max}$) is much smaller than the difference in $TS_{25}\times TEl$ between 1.5% and 5% Mn steels ($\Delta TS_{25}\times TEl$). The difference is caused by a difference in the volume fraction of the retained austenite. Therefore it is considered that higher $TS_{25}\times H_{max}$ values at $T_P^* = 150\text{-}300°C$ for 5% Mn steel are associated with the TRIP effect resulting from high volume fraction and high mechanical stability of retained austenite, although the effect of the retained austenite fraction is weaker than that in the case of $TS_{25}\times TEl$. Fig. 11 shows that the thickness strains of 5% Mn steel are greater than those of 1.5% Mn steel, with smaller $\Delta\varepsilon_t$. This may also contribute to the high $TS_{25}\times H_{max}$ of 5% Mn steel.

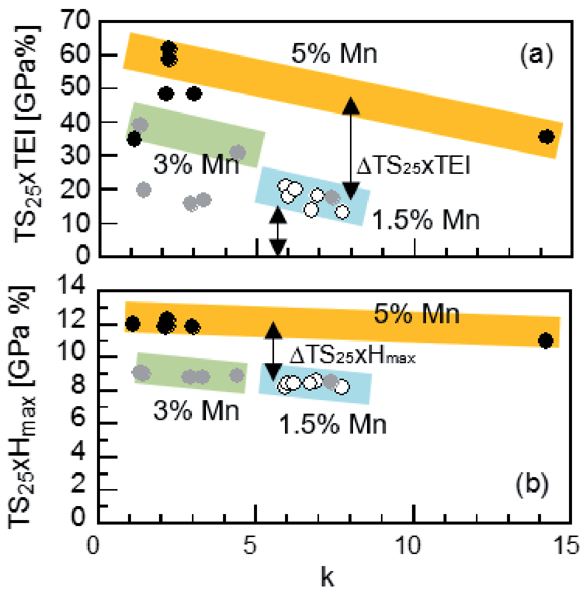

Fig. 13. Relationships between (a) $TS_{25}\times TEl$ and (b) $TS_{25}\times H_{max}$, and k for 1.5 (○), 3 (●) and 5% (●) Mn steels

As mentioned the above, the $\Delta TS_{25}\times H_{max}$ was smaller than the $\Delta TS_{25}\times TEl$. In case of stretch forming, applied mean normal stress σ_m in equi-biaxial tension is higher by $\sigma_N/3$ (σ_N: mean flow stress obtained as (YS+TS)/2) than that in uniaxial tension under a constant equivalent plastic. When 5% Mn steel was stretch-formed at 200°C, the mean normal stress increases by 266 MPa using YS and TS in Table 2. This high mean normal stress may promote void initiation and growth at interface between matrix and strain-induced martensite, and consequently decreases $\Delta TS_{25}\times H_{max}$ in comparison with $\Delta TS_{25}\times TEl$.

4.2. Peak temperature for stretch-formability of 5% Mn steel

Peak temperature for H_{max} of 5% Mn steel was $T_P^* = 150\text{-}300°C$, which was higher than that ($T_P = 150\text{-}200°C$) for TEl [36]. According to Sugimoto et al. [4], T_P agrees well with T_S corresponding to minimum k in the case of 0.2%C-(1.0-2.5)%Si-(1.0-2.0)%Mn TPF steels (Fig. 14(a)). For H_{max}, T_S rises to T_S^* because the high mean normal stress apparently increases M_S of retained austenite by ΔM_S. In this case, T_S^* agrees with T_P^* (= $T_P + \Delta T_P$). Simultaneously, stretch forming increases k on the whole. T_P^* of 5% Mn steel is close to an empirical line (equi-biaxial tension; solid line) in Figure 14(b). Therefore, high T_P^* of 5% Mn steel is considered to be decided by ΔM_S resulting from high applied mean normal stress in equi-biaxial tension.

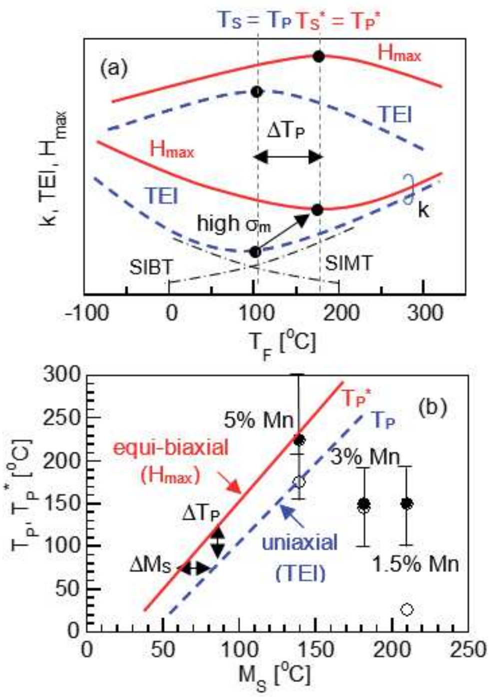

Fig. 14. (a) Schematic diagram of forming-temperature dependences of k, TEl, and H_{max} and (b) peak forming temperatures (T_P, T_P^*) for TEl (○) and H_{max} (●) of 1.5, 3 and 5% Mn steels as a function of M_S of retained austenite. In (a), T_S and T_S^* are temperatures corresponding to minimum k values in uniaxial and equi-biaxial tensions, respectively. In (b), dotted and solid lines denote T_P-M_S and T_P^*-M_S of 0.2%C-(1.0-2.5)%Si-(1.0-2.0)%Mn TPF steels. "SIMT" and "SIBT" refer to the strain-induced α'-martensite and bainite transformations, respectively

M_S of the retained austenite can be calculated using the following equation [42],

$$Ms\,[°C] = 550 - 350\times C\% - 40\times Mn\% - 35\times V\% - 20\times Cr\% - 17\times Ni\% - 10\times Cu\% - 10\times Mo\% - 10\times W\% - 0\times Si\% + 15\times Co\% + 30\times Al\%, \quad (2)$$

where *C%*, *Mn%*, *V%*, *Cr%*, *Ni%*, *Cu%*, *Mo%*, *W%*, *Si%*, *Co%*, and *Al%* are in mass% of individual elements. To calculate M_S, the measured carbon concentration ($C\gamma_0$) is substituted as *C%* in Eq. (2). *Mn%* is assumed to be 1.5 times the Mn content [4,38,43,44]. The above ΔM_S can be computed as follows. If M_S of retained austenite is assumed to increase by 6.7°C per applied mean normal stress of 100 MPa [45], then ΔM_S is calculated to be around 18°C using 266 MPa calculated at 4.1. This ΔM_S corresponds to the difference in temperature between T_P-M_S lines (ΔT_P = 20-30°C) in uniaxial and equi-biaxial tension.

T_P^*s of 1.5 and 3% Mn steels are far away from the solid line. This reason is in consideration.

5. Conclusions

The warm stretch-formability of 0.2%C-1.5%Si-(1.5-5.0)% Mn TRIP-aided steels was investigated. Additionally, the relationship between the warm formability and the characteristics of the retained austenite was determined.

- The stretch formability of 5% Mn steel was considerably increased by warm forming at 150 to 300°C, with a decrease in P_{max}. The warm stretch-formability increased with increasing Mn content.
- The superior warm stretch-formability was mainly due to a large amount of retained austenite and its stabilization that suppresses considerably void initiation and growth at the interface between the matrix and transformed martensite, as well as fine matrix structure.
- High peak temperature for stretch-formability of 5% Mn steel was associated with M_S of the retained austenite and high applied mean normal stress on stretch forming.

References

[1] V.F. Zackay, E.R. Parker, D. Fahr, R. Bush, The enhancement of ductility in high-strength steels, Transactions of American Society for Metals 60 (1967) 252-259.

[2] O. Matsumura, Y. Sakuma, Y. Ishii, J. Zhao, Effect of retained austenite of formability of high strength steel sheet, The Iron and Steel Institute of Japan International 32 (1992) 1110-1116.

[3] S. Hiwatashi, M. Takahashi. T. Katayama, M. Usuda, Effect of deformation-induced transformation on deep drawability: forming mechanism of TRIP type high-strength steel sheet, Journal of The Japan Society for Technology and Plasticity 35 (1994) 1109-1114.

[4] K. Sugimoto, M. Kobayashi, A. Nagasaka, S. Hashimoto, Warm stretch-formability of TRIP-aided dual-phase sheet steels, ISIJ International 35 (1995) 1407-1414.

[5] A. Nagasaka, K. Sugimoto, M. Kobayashi, S. Hashimoto, Effect of warm forming on stretch-flangeability of a TRIP-aided dual-phase steel, Tetsu-to-Hagane 83 (1997) 335-340 (in Japanese).

[6] A. Nagasaka, K. Sugimoto, M. Kobayashi, H. Shirasawa, Effects of second phase morphology on warm stretch-flangeability of TRIP-aided dual-phase sheet steels, Tetsu-to-Hagane 84 (1998) 218-223(in Japanese).

[7] K. Sugimoto, A. Nagasaka, M. Kobayashi, S. Hashimoto, Effects of retained austenite on warm stretch-flangeability of TRIP-aided dual-phase sheet steels, The Iron and Steel Institute of Japan International 39 (1999) 56-63.

[8] L. Wang, J.G. Speer, Quenching and partitioning steel heat treatment, Metallography, Microstructure, and Analysis 2 (2013) 268-281.

[9] K. Sugimoto, J. Sakaguchi, T. Iida, T. Kashima, Stretch-flangeability of TRIP type bainitic sheet steels, The Iron and Steel Institute of Japan International 40 (2000) 920-926.

[10] K. Sugimoto, R. Kikuchi, S. Hashimoto, Development of formable high strength low alloy TRIP steels with annealed martensite matrix, Steel Research 73 (2002) 253-258.

[11] K. Sugimoto, M. Tsunezawa, T. Hojo, S. Ikeda, Ductility of 0.1-0.6C-1.5Si-1.5Mn ultra high-strength low-alloy TRIP-aided sheet steels with bainitic ferrite matrix, The Iron and Steel Institute of Japan International 44 (2004) 1608-1614.

[12] K. Sugimoto, M. Murata, T. Muramatsu, Y. Mukai, Formability of C-Si-Mn-Al-Nb-Mo ultra high-strength TRIP-aided steels, The Iron and Steel Institute of Japan International 47 (2007) 1357-1362.

[13] A. Grajcar, Determination of the stability of retained austenite in TRIP-aided bainitic steel, Journal of Achievements in Materials and Manufacturing Engineering 20 (2007) 111-114.

[14] J. Kobayashi, D.V. Pham, K. Sugimoto, Stretch-flangeability of 1.5GPa grade TRIP-aided martensitic cold rolled sheet steels, Steel Research International (Special ed. for ICTP 2011) (2011) 598-603.
[15] J. Kobayashi, S. Song, K. Sugimoto, Ultra high-strength TRIP-aided martensitic steels, The Iron and Steel Institute of Japan International 52 (2012) 1124-1129.
[16] J. Kobayashi, D.V. Pham, K. Sugimoto, Stretch-flangeability and bendability of a 0.2C-1.5Si-1.5Mn-0.05Nb ultra high-strength TRIP-aided martensitic sheet steel, Steel Research International (Special ed. for Metal Forming 2012) (2012) 883-886.
[17] D.V. Pham, J. Kobayashi, K. Sugimoto, Effects of microalloying on stretch-flangeability of ultrahigh-strength TRIP-aided martensitic steel sheets, The Iron and Steel Institute of Japan International 54 (2014) 1943-1951.
[18] K. Sugimoto, A.K. Srivastava, Microstructure and mechanical properties of a TRIP-aided martensitic steel, Metallography, Microstructure & Analysis 4 (2015) 344-354.
[19] J.G. Speer, D.V. Edmonds, F.C. Rizzo, D.K. Matlock, Partitioning of carbon from supersaturated plates of ferrite with application to steel processing and fundamentals of the bainite transformation, Current Opinion in Solid State & Materials Science 8 (2004) 219-237.
[20] D. Fan, N. Fonstein, H. Jun, Effect of microstructure on tensile properties and cut-edge formability of DP, TRIP, Q&T and Q&P steels, Iron & Steel Technology Transactions 13 (2016) 180-185.
[21] R.L. Miller, Ultrafine-grained microstructures and mechani-cal properties of alloy steels, Metallurgical Transactions 3 (1972) 905-912.
[22] T. Furukawa, Dependence of strength-ductility characteristics on thermal histry in low carbon, 5 wt-%Mn steels, Materials Science and Technology 5 (1989) 465-470.
[23] T. Furukawa, H. Huang, O. Matsumura, Effects of carbon content on mechanical properties of 5%Mn steels exhibiting transformation induced plasticity, Materials Science and Technology 10 (1994) 964-970.
[24] H. Haung, O. Matsumura, T. Furukawa, Retained austenite in low carbon, manganese steel after intercritical heat treatment, Materials Science and Technology 10 (1994) 621-626.
[25] H. Aydin, E. Essadiqi, I. Jung, S. Yue, Development of 3rd generation AHSS with medium Mn content alloying compositions, Materials Science and Engineering A 564 (2013) 501-508.
[26] W. Bleck, D. Raabe eds., Proceedings of 2nd International Conference on High Managanese Steel (HMnS 2014), Aachen, Geramany, 2014.
[27] S. Lee, B.C. De Cooman, On the selection of the optimal intercritical annealing temperature for medium Mn TRIP steel, Metallurgical and Materials Transactions A 44 (2013) 5018-5024.
[28] S. Chen, J. Hu, X. Zhang, H. Dong, W. Cao, High ductility and toughness of a micro-duplex medium-Mn steel in a large temperature range from -196°C to 200°C, Journal of Iron and Steel Research, International 22 (2015) 1126-1130.
[29] R. Rana, P.J. Gibbs, E. De Moor, J. G. Speer, D.K. Matlock, A composite modeling analysis of the deformation behavior of medium manganese steels, Steel Research International 86 (2015) 1139-1150.
[30] S. Kang, J.G. Speer, D. Krizan, D.K. Matlock, E. De Moor, Prediction of tensile properties of intercritically annealed Al-containing 0.19C-4.5Mn (wt%) TRIP steels, Materials and Design 97 (2016) 138-146.
[31] K. Sugimoto, K. Koyama, H. Tanino, Formability of 0.2%C-1.5%Si-(1.5-5)%Mn TRIP-aided annealed martensitic steels, Proceedings of Materials Science and Technology 2015 (MS&T 2015), AIST, Warrendale, PA, USA, 2015, 859-868.
[32] T. Hanamura, S. Torizuka, A. Sunahara, M. Imagunbai, H. Takechi, Excellent total mechanical-properties - balance of 5% Mn, 30000 MPa% steel, The Iron and Steel Institute of Japan International 51 (2011) 685-687.
[33] H. Tanino, M. Horita, K. Sugimoto, Impact toughness of 0.2%C-1.5%Si-(1.5-5)%Mn transformation-induced plasticity-aided steels with an annealed martensite structure matrix, Metallurgical and Materials Transactions A 47 (2016) 2073-2079.
[34] K. Sugimoto, H. Tanino, J. Kobayashi, Impact toughness of 0.2%C-1.5%Si-(1.5-5.0)%Mn TRIP-aided martensitic sheet steels, Steel Research International 86 (2015) 1151-1160.
[35] O. Grassel G. Frommeyer, Effect of martensitic phase transformation and deformation twinning on mechanical properties of Fe-Mn-Si-Al steels, Materials Science and Technology 14 (1998) 1213-1217.
[36] K. Sugimoto, H. Tanino, J. Kobayashi, Warm ductility of 0.2%C-1.5%Si-5%Mn TRIP-aided steel, Materials Science and Engineering A to be submitted.
[37] I. Tsukatani, S. Hashimoto, T. Inoue, Effects of silicon and manganese addition on mechanical properties of high-strength hot-rolled sheet steel containing retained

austenite, The Iron and Steel Institute of Japan International 31 (1991) 992-1000.
[38] K. Sugimoto, N. Usui, M. Kobayashi, S. Hashimoto, Effects of volume fraction and stability of retained austenite on ductility of TRIP-aided dual-phase steels, The Iron and Steel Institute of Japan International 32 (1992) 1311-1318.
[39] K. Sugimoto, M. Kobayashi, S. Hashimoto, Ductility and strain-induced transformation in a high strength TRIP-aided dual-phase steel, Metallurgical Transactions A 23 (1992) 3085-3091.
[40] D.J. Dyson, B. Holmes, Effect of alloying additions on the lattice parameter of austenite, Journal of the Iron and Steel Institute 208 (1970) 469-474.
[41] Y. Tomota, Phase Transformation, microstructure, and mechanical behavior in Fe-Mn alloys, Tetsu-to-Hagane 77 (1991) 315-325.
[42] O. Miyagawa, Iron and Steel Material, Asakura Publishing Co. Ltd., Tokyo, 1982, 119.
[43] J.B. Gilmour, G.R. Purdy, J.S. Kirkaldy, Thermodynamics controlling the proeutectoid ferrite transformations in Fe-C-Mn alloys, Metallurgical Transactions 3 (1972) 1455-1464.
[44] G.R. Speich, V.A. Demarest, R.L. Miller, Formation of austenite during intercritical annealing of dual-phase steels, Metallurgical Transactions A 12 (1981) 1419-1428.
[45] S.V. Radcliffe, M. Schatz, The effect of high pressure on the martensitic reaction in iron-carbon alloys, Acta Metallurgica 10 (1962) 201-207.