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Effect of bainitic transformation on mechanical properties of 0.6C–Si–Mn steel

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The mechanical properties of 0.6C–Si–Mn steel transformed isothermally in the bainitic temperature region (593 and 648 K) were investigated. The mechanical properties of the steels were improved with increasing bainite and retained austenite and the corresponding decrease in martensite. Marked benefits of the mechanical properties were obtained for the steels containing the maximum content of retained austenite in the bainite matrix, independent of transformation temperature. For isothermal transformation at 593 K, the 0.2% yield stress, σ_y, ultimate tensile stress, σ_u, and notch tensile stress (NTS) were improved significantly, while the advantage of the per cent elongation and Charpy 2 mm V-notch (CVN) impact energy was relatively small. As a result of isothermal transformation at 648 K, the per cent elongation and CVN impact energy were dramatically improved, while the superiority of σ_y, σ_u and NTS was not much greater than isothermal transformation at 593 K. Compared to 0.6C steels transformed isothermally at the same temperatures, in which little appreciable retained austenite was found, the isothermally transformed steels having a microstructure consisting of bainite and retained austenite improved the mechanical properties remarkably. These results are described and discussed.

1. Introduction

Retained austenite has frequently been encountered in commercial heat treatment and great improvements in ductility and toughness, have been associated with the morphology (amounts, size, shape and distribution) of the retained austenite. Therefore, the retained austenite has been produced in a deliberate attempt to improve the mechanical properties of the steels. Much attention has recently been paid to isothermal transformation in the bainitic temperature region of steels containing high silicon, in which the retention of a large amount of retained austenite is encouraged, in conjunction with carbon-free upper bainite ferrite [1–5].

In such situations, a series of studies has been conducted to clarify the relationship between the microstructure and mechanical properties of bainite-transformed Si–Mn steels. In the previous work [6], the effect of bainitic transformation on the microstructure of Si–Mn steels with similar silicon and manganese levels and with carbon contents ranging from 0.25–0.75 wt % was reported. The significant results obtained are as follows: (1) there was an optimum transformation time to produce the maximum content of the retained austenite independent of transformation temperature; (2) the microstructure consisted of carbon-free upper bainite whose individual ferrite was separated by the "thin-film" type of retained austenite independent of temperature, while the "blocky" type of austenite increased with increasing temperature; (3) the thermal and mechanical stabilities of the retained austenite were improved with decreasing temperature, leading to increased carbon content in the retained austenite.

In the present work, commercial 0.6C–Si–Mn and 0.6C steels have been studied to determine the effect of bainitic transformation on the mechanical properties of Si–Mn steels.

2. Experimental procedure

Commercial 0.6C–Si–Mn and 0.6C steels, which were air-melted and vacuum-degassed, were used in this investigation. The steels were obtained as hot-rolled plates of 10 mm. The chemical composition and M_s temperature of the steels are given in Table I. Test specimens with their longitudinal axes parallel to the rolling direction were machined from the plates. Each specimen was fully annealed.

The heat-treatment schedules in this investigation are given in Table II. All the steels were austenitized in an argon-atmosphere tube furnace and isothermal transformation was conducted in a salt bath that had a thermal capacity sufficient to avoid appreciable temperature change during the operation. Tempering was carried out in an oil bath.

Mechanical properties were determined through tensile and Charpy impact tests. Tensile properties were determined at ambient temperature (293 K) using an Instron machine at a constant strain rate of

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TABLE I Chemical composition and M_s temperature of steels investigated

Designation of steel	Chemical composition (wt %)					M_s[a]
	C	Si	Mn	P	S	(K)
0.6C–Si–Mn	0.60	1.65	0.80	0.019	0.009	523
0.6C	0.60	0.18	0.64	0.016	0.012	588

[a] M_s temperature was determined by standard dilatometric measurement.

TABLE II Heat-treatment schedules

Designation of steel	Heat treatment
0.6C–Si–Mn	Austenitize at 1143 K for 3.6 ks, transform isothermally at 593 K for (0–1.3.6 ks) and 648 K for (0–1.8 ks), quench in water, temper at 523 K for 7.2 ks
0.6C	Austenitize at 1143 K for 3.6 ks, transform isothermally at 593 and 648 K for 7.2 ks, quench in water

$6.70 \times 10^{-4}\ s^{-1}$. Smooth tensile specimens (pin-load type) with a gauge length of 12.5 mm and a gauge section of 1.5 mm × 4.0 mm and notch tensile specimens (pin-load type) with a gauge length of 12.5 mm and a net cross-section under the notches of 1.5 mm × 4.0 mm with 2 mm V-notch in both shorter sides. The subsize Charpy 2 mm V-notch (CVN) specimens (5 mm thick) were broken at 293 K in a Charpy impact machine with maximum capacity of 49 J. Before heat treatment, all the specimens were machined to dimensions slightly larger than the desired final size. After heat treatment, the specimens were ground to their final dimensions. The V-notches for notch-tensile and CVN specimens were prepared using an electrospark machine to introduce a notch of depth 2 mm.

The microstructure was categorized using optical microscopy (OM) and X-ray diffraction (XRD). The bainitic structure was delineated by etching in a 5 wt % picric acid solution. The volume fraction of bainite was determined by a point count [7, 8], in which the specimen is viewed directly on the optical microscope stage. The retained austenite content was measured by XRD using Miller's technique [9] of rotating and tilting the sample surface about an incident beam of MoK_α (using a zirconium filter). The sample surface was electropolished in a mixed solution of phosphoric and chromic acids. A scanning speed of $0.003\ deg\ s^{-1}$ was used and the combination of peaks chosen for analysis was (2 0 0)α, (2 1 1)α, (2 0 0)γ, (2 2 0)γ and (3 1 1)γ.

Fractography was performed on fresh fracture surfaces from the smooth tensile specimens using the scanning electron microscope (SEM).

3. Results and discussion

3.1. Microstructural analysis

Fig. 1 shows transformation-time dependence of the portion of the various microconstituents observed

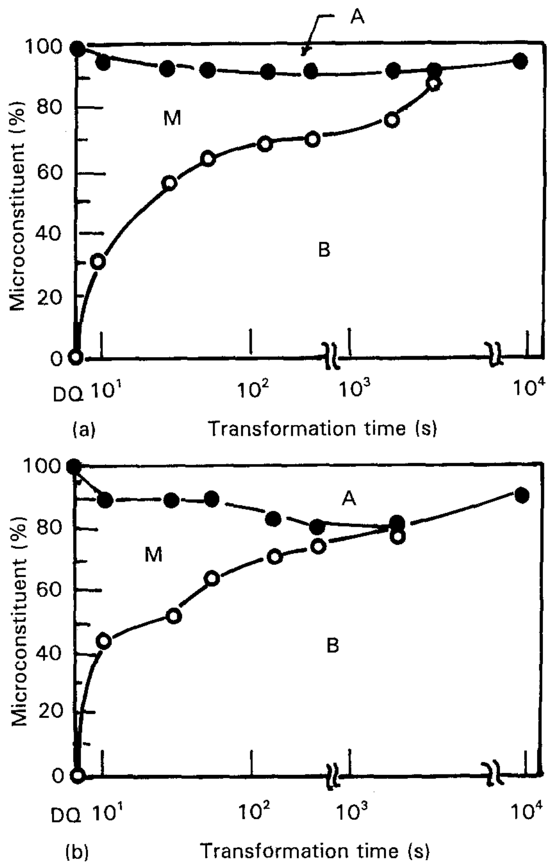

Figure 1 Microconstituents after partial isothermal transformation of 0.6C–Si–Mn steel at (a) 593 K and (b) 648 K. B, M and A show bainite, martensite and retained austenite, respectively. DQ indicates direct quench.

after isothermal transformation at 593 and 648 K. Each figure presents three regions, and 0 s transformation time in each figure shows direct quenching (DQ). Region B shows the volume percentage of bainite formed as a function of transformation time at 593 and 648 K, as determined by metallographic point-counting technique. Region A shows, as a function of transformation time at 593 and 648 K, the volume percentage of retained austenite, as determined by XRD. Region M shows the volume percentage of martensite. The volume percentage was found by subtracting from 100 vol % the sum of the percentage given by the regions A and B. The significant results obtained from Fig. 1 are as follows: (1) a triple phase (martensite, bainite and retained austenite) microstructure can be produced by isothermal transformation (IT) for a short time followed by water quenching; (2) the mixed structure of only bainite and retained austenite can be produced by IT for a long time; (3) the transformation time to produce the mixed structure with bainite and maximum retained austenite decreased from 3000 s to 300 s as transformation temperature increased from 593 K to 648 K; (4) the maximum retained austenite content increased from 9.0 vol % to 19.4 vol % as the temperature increased from 593 K to 648 K. The OM revealed that for IT at 593 K, each of the bainite ferrites appeared separately and partitioned martensite finely (Fig. 2a); whereas, for IT at 648 K, closely spaced bainite ferrite aggregates appeared (Fig. 2b). As details of the morphology of the

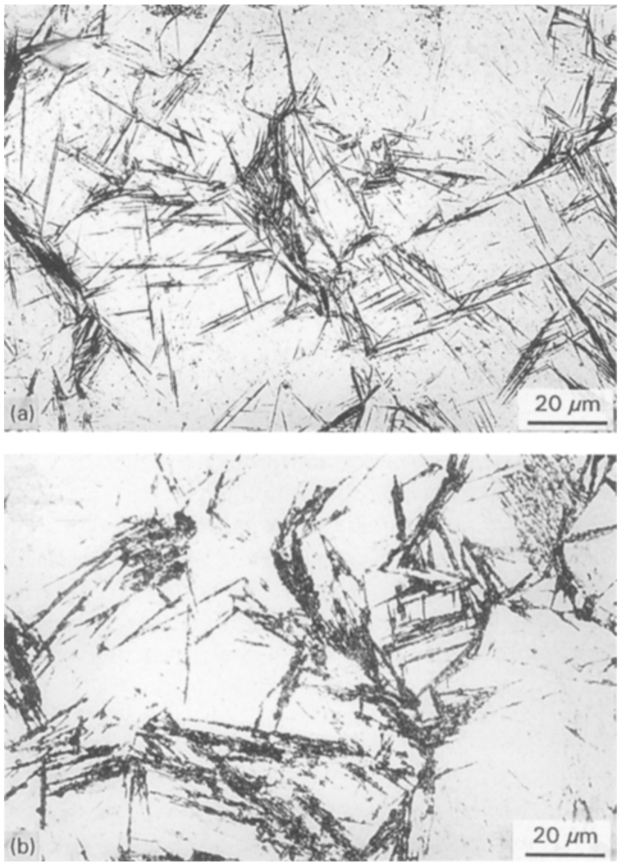

Figure 2 Optical microscopy of bainitic structure of 0.6C–Si–Mn steel transformed isothermally (IT steel). (a) IT steel at 593 K for 10 s; (b) IT steel at 643 K for 10 s.

bainite and retained austenite of the IT steels have been presented in the previous paper [6], only the experimental results are described here. TEM revealed that the IT produced a carbon-free upper bainite whose individual ferrite plate was separated by the "thin film" type of retained austenite independent of transformation temperature. OM revealed that the "blocky" type of austenite was found, independent of transformation temperature and the average size and distribution of the "blocky" type of austenite were larger and heterogeneous, respectively, as transformation temperatures increased. For martensitic structure, lath martensite, involving relatively large amounts of twin plates, was observed, as described elsewhere [10]. For 0.6C steel, IT at 593 K leads to the formation of lower bainite of acicular form, whereas IT at 648 K produced upper bainite in masses. The details of the morphology were described elsewhere [6, 11].

3.2. Mechanical properties

The mechanical properties of IT steel at 593 and 648 K were investigated. The results are listed in Table III. In this table, the results obtained by direct quenching followed by tempering (DQT) of 0.6C–Si–Mn steel and IT at 593 and 648 K in 0.6C steel (designated 0.6C–593 K–IT and 0.6C–648 K–IT steels, respectively) are also involved. The mechanical properties of the IT steels at 593 and 648 K were improved with increasing bainite and retained austenite content and a corresponding decrease in martensite, whereas DQT steel had a very detrimental effect on the mechanical properties. Marked benefits of the mechanical properties were obtained for the steels containing the maximum content of retained austenite in the bainite matrix, independent of transformation temperature. For IT steel at 593 K, 0.2% yield stress, σ_y, ultimate tensile stress, σ_u, and notch tensile stress (NTS) increased significantly, while the advantage of uniform and total elongations (UE and TE, respectively) and CVN impact energy (Ech) were relatively small. As a result of IT at 648 K, the UE, TE and Ech were dramatically improved, while the superiority of σ_y and σ_u was not as great as that of the IT at 593 K. Compared to 0.6C–593 K–IT or 0.6C–648 K–IT

TABLE III Mechanical properties of 0.6C–Si–Mn and 0.6C steels isothermally transformed at 598 and 643 K

Designation of steel	Temp. (K)	Time (s)	B[a] (vol %)	RA[b] (vol %)	σ_y[c] (MPa)	σ_u[d] (MPa)	UE[e] (%)	TE[f] (%)	NTS[g] (MPa)	Ech[h] (J)
0.6C–Si–Mn	(DQT)[i]		–	–	–	1197	–	–	953	3.6
	593	10	35.6	5.2	–	1971	–	–	1203	3.7
	593	30	55.0	7.1	–	1425	1.0	1.0	1457	4.0
	593	300	70.1	9.0	1148	1606	3.7	6.5	1917	11.2
	593	3600	91.0	9.0	1203	1641	4.0	6.9	2016	16.8
	648	10	42.9	9.9	–	1656	–	–	1490	3.8
	648	30	53.9	11.2	1624	1640	2.1	2.1	1663	6.8
	648	150	72.7	17.2	1187	1557	5.3	11.5	1724	17.8
	648	300	73.3	19.3	1118	1421	7.0	14.3	1615	20.0
	648	1800	80.8	19.4	1223	1382	8.9	18.8	1702	28.0
0.6C	593	7200	100	–	914	1113	1.9	3.8	1432	10.3
	648	7200	100	–	686	970	5.8	10.3	1083	12.3

[a] B, volume fraction of bainite.
[b] RA, retained austenite content.
[c] σ_y, 0.2% yield stress.
[d] σ_u, ultimate tensile stress.
[e] UE, uniform elongation.
[f] TE, total elongation.
[g] NTS notch tensile stress.
[h] Ech, Charpy 2 mm V-notch impact energy.
[i] DQT direct quenching treatment.

steels, the IT steel having a microstructure consisting of only bainite and retained austenite, improved significantly not only σ_y and σ_u, but also UE, TE, NTS and Ech.

3.3. Fractography

It is well known that fractography directly describes the situation of fracture process and provides valuable evidence concerning the cause of failure. Therefore, attention was paid to fracture surfaces from the smooth tensile specimens of the IT steels at 593 and 648 K. The results were also compared with those of DQT, 0.6C–593 K–IT and 0.6C–643 K–IT steels. Figs 3 and 4 show the representative results. Fractography revealed that for the DQT steel, a very large brittle fracture facets were often observed (Fig. 3a). Fractography also revealed that for the IT steel at 593 K, fine dimple fracture was frequently found and increased with increasing retained austenite content (Fig. 3b), whereas for IT steels at 648 K steel, the refinement of fracture facets occurred with increasing retained austenite content, while fine dimple fracture was found as well (Fig. 3c). On the other hand, for the 0.6C–593 K–IT and 0.6C–648 K–IT steels containing little retained austenite, fracture surfaces consisted of quasi-cleavage facets and dimple fracture (Fig. 4a and b). The above results confirmed that retained austenite is responsible for the improved ductility of the IT steels. However, the fracture profiles suggested that the retained austenite has a differing response to the effect on the ductility as transformation temperature increased from 593 K to 648 K. From the present results, together with the previous work [6], it may safely be said that for the IT steel at 593 K, the improved ductility is attributed to the relaxation or crack-arresting effects by mechanically stable thin films of austenite [12–15]. However, for the IT steel at 648 K, the improved ductility could not be due to such effects.

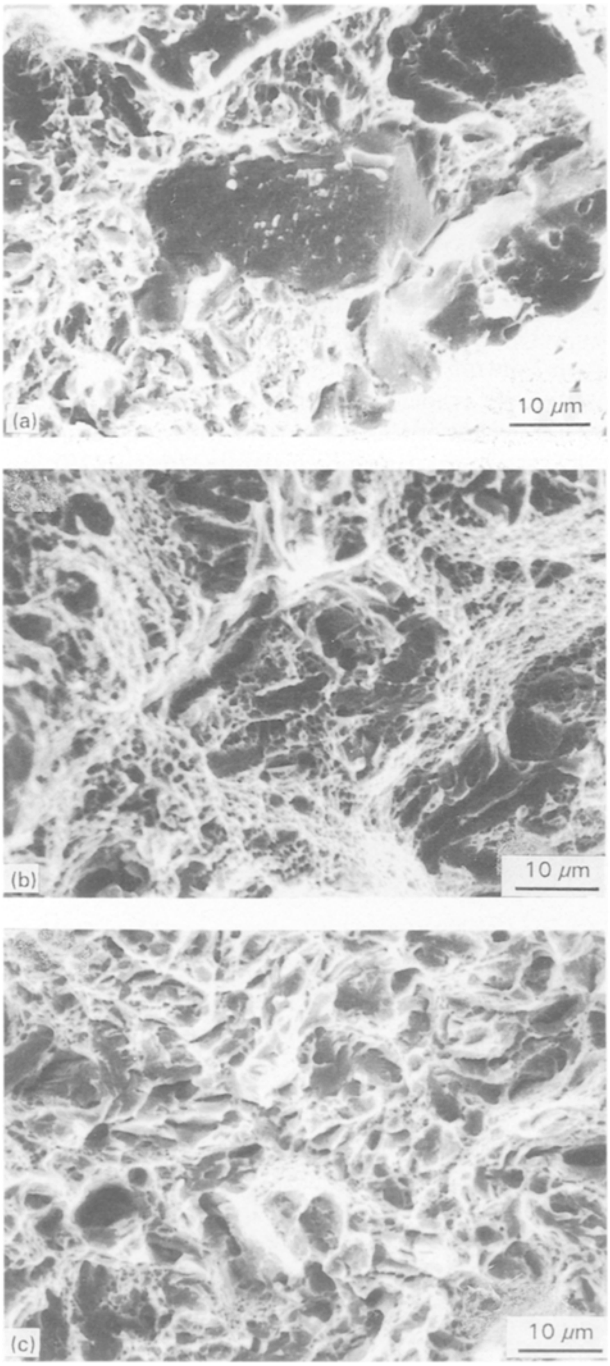

Figure 3 Typical scanning electron micrographs of fracture surfaces from smooth tensile specimens of 0.6C–Si–Mn steel. (a) DQT steel; (b) IT steel at 593 K for 3600 s; (c) IT steel at 593 K for 3600 s; (b) IT steel at 648 K for 1800 s.

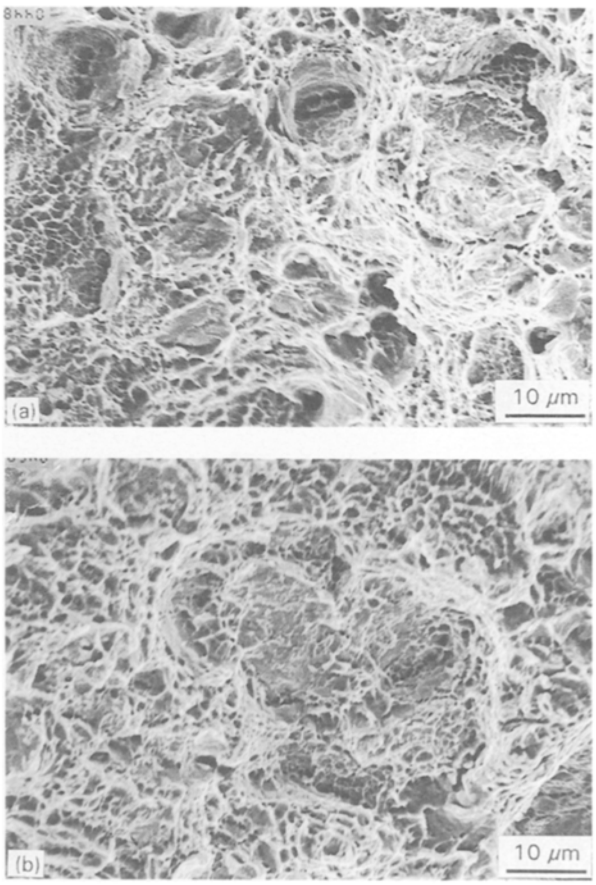

Figure 4 Typical scanning electron micrographs of fracture surfaces from smooth tensile specimens of 0.6C steel transformed isothermally (0.6C–IT steel). (a) 0.6C–IT steel at 593 K for 7200 s; (b) 0.6C steel at 648 K for 7200 s.

3.4. Work-hardening rate and retained austenite

In order to clarify the effect of retained austenite on the improved ductility of the IT steel at 648 K, the true stress, σ_t, and the work-hardening rate, $d\sigma_t/d\varepsilon_t$, of the IT steel at 648 K during tensile deformation were plotted as a function of the true strain, ε_t (Fig. 5). The $d\sigma_t/d\varepsilon_t$ in σ_t–ε_t curve was evaluated by means of a graphical solution using a half-silvered mirror, which is one of the potential techniques [16]. The results were compared with those of 0.6C–648 K–IT steel. Compared to the 0.6C–648 K–IT steel, the work-hardening rate and the proportion of the decrease in the work-hardening rate in the IT steel at 648 K were higher and smaller, respectively. It is well known that stable plastic flow will continue until the true stress exceeds the rate at which the material undergoes a work-hardening condition [17]. As the work-hardening rate is higher and the proportion of decrease in the work hardening is smaller, the condition at which necking begins, that is $d\sigma_t/d\varepsilon_t = \sigma_t$, is shifted to the higher strain side and, consequently, the ductility increases [18, 19]. Therefore, the results in Fig. 5 suggest strongly that the improvement in the ductility of the IT steel at 648 K is due to the effect of transformation induced plasticity (TRIP) [20] which occurred during plastic deformation. In order to confirm further the fact that the effect of TRIP occurred, the effect of cold-rolling reduction on the Vickers hardness and retained austenite content was investigated for the IT steel at 648 K (Table IV). The results were also compared with those of 0.6C–648 K–IT steel. It was found that for IT steel at 648 K, the significant increase in the hardness and the corresponding decrease in retained austenite content were found with decreasing cold-rolling reduction, whereas for the 0.6C–648 K–IT steel, the increase in the hardness and the decrease in the retained austenite content were very small compared to the IT steel at 648 K. It was concluded from the above results, together with fractography, that the improvement in the mechanical properties of the IT steel at 648 K can be attributed to the fact that the effect of TRIP by the austenite occurred effectively during plastic deformation. One may safely say that the above results and arguments for the improved ductility can be also applied to the explanation of the improvements in the mechanical properties such as NTS and Ech of the IT steels.

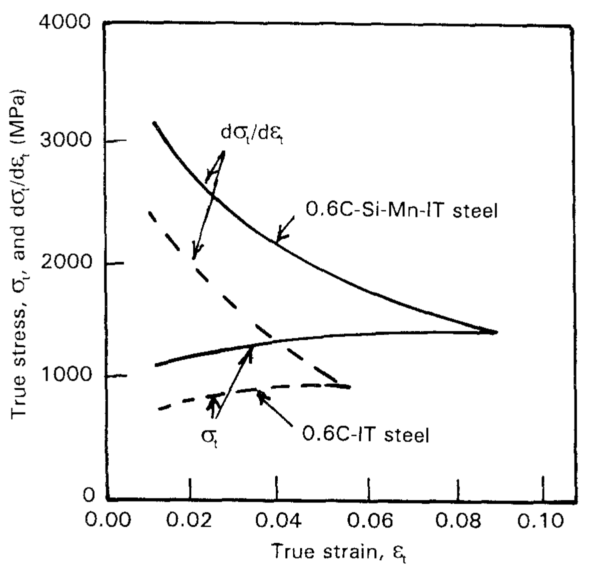

Figure 5 True stress, σ_t, and work-hardening rate, $d\sigma_t/d\varepsilon_t$, of 0.6C–Si–Mn–IT steel (IT at 648 K for 1800 s) and 0.6C–IT steel (IT at 648 K for 7200 s) during tensile deformation as a function of true strain, ε_t.

TABLE IV Effect of cold-rolling reduction on hardness and retained austenite content of 0.6C–Si–Mn and 0.6C steels transformed isothermally at 648 K

CRR[a] (%)	0.6C–Si–Mn steel		0.6C steel	
	MVH[b] (H_v)	RA (vol %)	MVH[b] (H_v)	RA (vol %)
0	418	19.4	302	Not evaluated
10	452	12.3	312	Not evaluated
20	468	8.9	318	Not evaluated
30	481	8.1	322	Not evaluated
40	502	6.8	325	Not evaluated
50	518	5.6	329	Not evaluated

[a] CRR, cold-rolling reduction.
[b] MVH, Vickers hardness.

In summary, the significant results concerning the mechanical properties of 0.6C–Si–Mn steel isothermally transformed in the bainitic temperature region obtained from the present work are that (1) the combinations of high strength with moderately improved ductility and notch toughness can be attained by lower temperature isothermal transformation in which the mechanically stable austenite appears, (2) the combinations of high ductility and high toughness with moderate strength can be attained by higher temperature isothermal transformation in which the effect of TRIP by the austenite occurs effectively during plastic deformation.

4. Conclusions

1. The mechanical properties of 0.6C–Si–Mn steel isothermally transformed at 593 and 648 K were improved with increasing bainite and retained austenite and the corresponding decrease in martensite.

2. Marked benefits of the mechanical properties were obtained for the steels containing the maximum content of retained austenite in the bainite matrix independent of transformation temperature.

3. For isothermal transformation at 593 K, the 0.2% yield stress, σ_y, ultimate tensile strength, σ_u, and notch tensile stress (NTS), were improved significantly, while the advantage in the per cent elongation and CVN impact energy was relatively small.

4. As a result of isothermal transformation at 648 K, the per cent elongation and CVN impact energy increased dramatically, while the superiority of the σ_y, σ_u and NTS was not so great as isothermal transformation at 593 K.

5. Compared to 0.6C steel transformed isothermally at the same temperatures, the 0.6C–Si–Mn steels having the mixed structure of bainite and

retained austenite, had remarkably improved mechanical properties.

6. The beneficial effect on the mechanical properties of the steel transformed isothermally at 593 K is due to the stress relaxation or crack-arresting effect by the mechanically stable thin-film type of austenite. The favourable effect on the mechanical properties of the steel transformed isothermally at 648 K is attributed to the effect of transformation induced plasticity by the austenite which occurred effectively during deformation.

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