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Effect of bainitic transformation on microstructure of Si–Mn steel

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Several Si–Mn steels with similar Si and Mn levels and carbon contents, ranging from 0.25 to 0.75 wt %, were studied to determine the effect of bainitic transformation on the microstructure of Si–Mn steel. The microstructure was categorized by optical metallography, scanning and transmission electron microscopy, and X-ray diffraction. The results showed the existence of an optimum transformation time to produce the maximum content of retained austenite, though the retention of a large amount of retained austenite was encouraged as a result of bainitic transformation. The microstructure consisted of carbon-free upper bainite whose individual ferrite was separated by the 'thin-film' type of retained austenite, while the 'blocky' type of austenite was also found. The results also showed that carbide precipitation occurred in the residual austenite after the optimum time, which decreased the retained austenite content. The retained austenite stability is discussed in relation to the carbon content and morphology of the retained austenite.

1. Introduction

Retained austenite is often produced in commercial heat treatments of steels and has a detrimental effect on the hardness of bearings or dimensions of tools or gauges. Therefore the presence of the retained austenite is not useful for components in which high hardness or dimensional precision is required. However, such austenite frequently results not only in improved ductility and toughness of structural low-alloy steels, but also in increased fatigue strength and wear resistance, if it appears in a suitable morphology in association with the matrix. Thus retained austenite has recently been produced in an attempt to improve the mechanical properties of steels.

Previous investigations [1–4] have shown that the presence of high levels of silicon in low-alloy steels, isothermally transformed in the bainitic temperature region, encourages the retention of a large amount of carbon-enriched austenite in conjunction with carbon-free upper-bainite ferrite, rather than the formation of carbides which has a detrimental effect on ductility and toughness. Subsequent microstructure–property work [5–8] has indicated that the retained austenite could produce significantly improved mechanical properties if it appeared a suitable morphology and had superior thermal and mechanical stability. However, the morphology and stability of retained austenite depend on alloying elements; transformation temperature; average carbon content before bainitic transformation; and the carbon content in the austenite. When these points are considered, the picture becomes more complicated.

In the present work, several Si–Mn steels with similar Si and Mn levels and carbon contents ranging from 0.25 to 0.75 wt% were studied to determine the effect of bainitic transformation on the microstructure of Si–Mn steel.

2. Experimental procedure

Several Si–Mn and plain carbon 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 Ms temperature of the steels are given in Table I. Test specimens with their longitudinal axis 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 with a sufficient thermal capacity to avoid appreciable temperature change during operation. The microstructure was categorized using optical metallography (OM), scanning and transmission electron microscopy (SEM, TEM), and X-ray diffraction (XRD). Thin foils for TEM were prepared by grinding to 0.1 mm thickness, then chemically thinning in a mixed solution of hydrofluoric acid and hydrogen peroxide, followed by electropolishing in a mixed solution of phosphoric and chromic acids. 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 Zr filter). The sample surface was electropolished in a mixed solution of phosphoric and chromic acids. A scanning speed of $0.003^\circ s^{-1}$ was used and the combination of peaks

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TABLE I Chemical composition and Ms temperature of steels investigated

Designation of steel	Chemical composition (wt%)					Ms* (K)
	C	Si	Mn	P	S	
25 CSM	0.25	1.65	0.80	0.017	0.009	643
41 CSM	0.41	1.60	0.83	0.018	0.008	553
60 CSM	0.60	1.65	0.80	0.019	0.009	523
75 CSM	0.75	1.60	0.88	0.018	0.008	512
60 C	0.60	0.18	0.64	0.016	0.012	588

* Ms temperature was determined by standard dilatometric measurement.

TABLE II Heat treatment schedules

Designation of steel	Heat treatment
25 CSM, 41 CSM, 60 CSM, 75 CSM	Austenitize at 1143 K for 3.6 ks, transform isothermally in bainitic temperature regions (598–723 K) for 0–10 ks, water quench.
60 C	Austenitize at 1143 K for 3.6 ks, transform isothermally at bainitic temperature of 673 K for 0–18 ks, water quench.

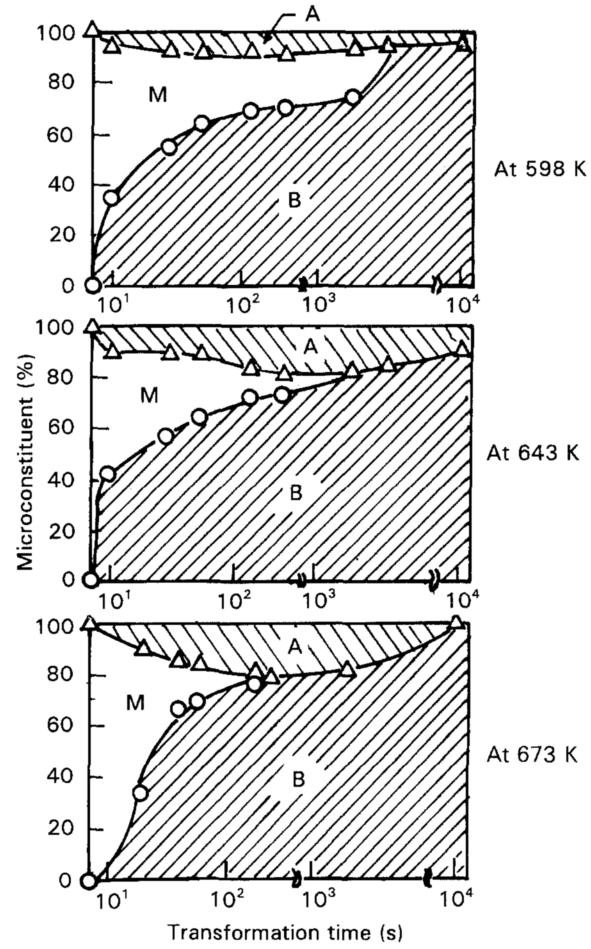

Figure 1 Microconstituents after partial isothermal transformation of 60 CSM steel. B, M and A show bainite, martensite and retained austenite, respectively.

chosen for analysis was (200)α, (211)α, (200)γ, (220)γ and (311)γ. The thermal stability of retained austenite was investigated by sub-zero and tempering treatments. In the sub-zero treatment, specimens were cooled at the required temperature by a refrigerant composed of a mixed solution of liquid nitrogen and petroleum ether. Tempering was done in a silicon oil. The mechanical stability of retained austenite was examined using tensile specimens with a gauge length of 12.5 mm and a cross section of 1.5 × 10 mm at a constant strain rate of 6.75×10^{-4} using an Instron machine. A critical discussion of the mechanical stability of the retained austenite was made on the basis of the ratio (%) of the retained austenite content of the gauge length (plastic strained by 3%) and that of the head of the specimens (not plastic strained). The carbon content of retained austenite was calculated by the following equation [10] based on a lattice parameter determined from (311)γ by XRD

$$c(\mathrm{wt}\%) = (a - 3.555)/0.0044 \qquad (1)$$

where c and a are the carbon content and lattice parameter, respectively.

3. Results and discussion

3.1. Microstructural analysis and characterization

The microconstituents of Si–Mn steels after partial isothermal transformation in bainitic temperature regions were investigated. Fig. 1 shows the results obtained for 60 CSM steel. As a bainitic transformation of the steel, the retention of a large amount of retained austenite was encouraged. However, the microstructural analysis revealed the existence of an optimum transformation time to produce the maximum retained austenite content, independent of transformation temperature. The optimum time decreased as transformation temperature increased. The analysis also revealed that the retained austenite content decreased after the optimum time, while the degree of the decrease was larger with higher transformation temperature. In order to clarify the unique bainitic-transformation behaviour of Si–Mn steel, the microstructure of 60 CSM steel was characterized by OM, SEM and TEM. The results were compared with those obtained by 60 C steel.

Fig. 2 shows typical OM micrographs of 60 C and 60 CSM steels, transformed isothermally at 673 K for a short time. OM revealed that for the 60 C steel, the bainite appeared as masses (Fig. 2a) and for the 60 CSM steel, individual bainitic ferrites were separated mutually (Fig. 2b). Their substructures were observed by TEM, which revealed that 60 C steel consisted of an upper bainite with an internal carbide stringer lying along the length of lathes (Fig. 3a), but 60 CSM steel produced a carbon-free upper bainite whose individual ferrite plate was separated by the 'thin-film' type of retained austenite (Fig. 3b). The former was due to the fact that carbide precipitation occurred in bainitic–ferrite boundaries as little carbon dissolves in the ferrite [11]. The latter is due to the fact that significant carbon enrichment of the residual austenite

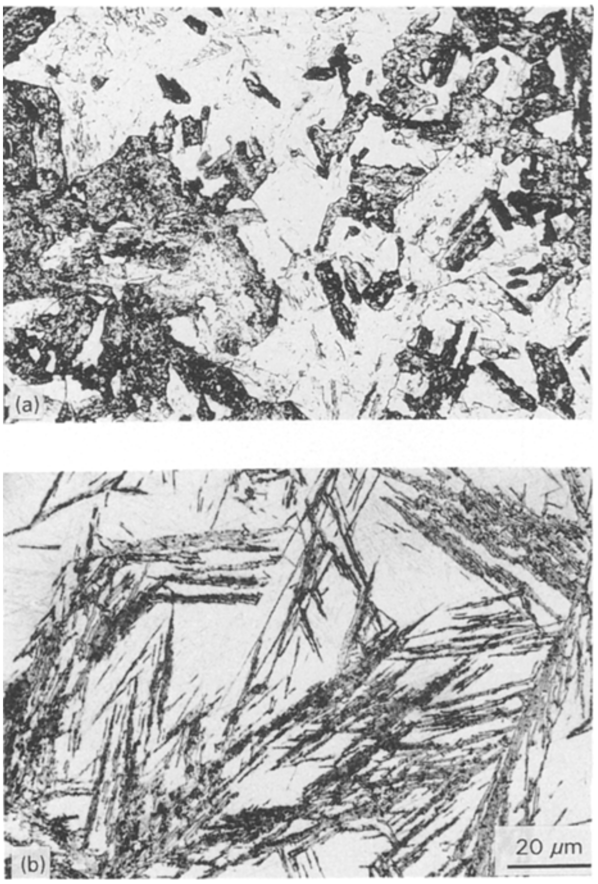

Figure 2 OM micrographs of bainitic structure of 60 C and 60 CSM steels, transformed isothermally (IT) at 673 K. Specimens were etched by 5 vol% nitrate alcohol solution. (a) 60 C steel (IT for 50 s); (b) 60 CSM steel (IT for 30 s).

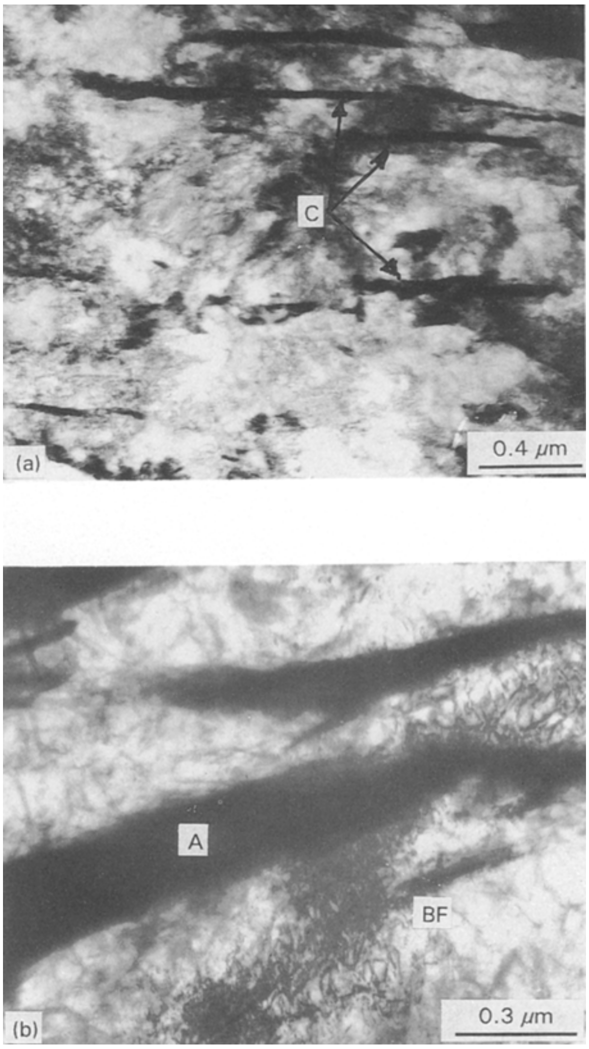

Figure 3 TEM micrographs of 60C and 60 CSM steels, IT at 673 K. (a) IT for 18 ks; (b) IT for 180 s. C, A and BF show carbide, retained austenite and bainite ferrite, respectively.

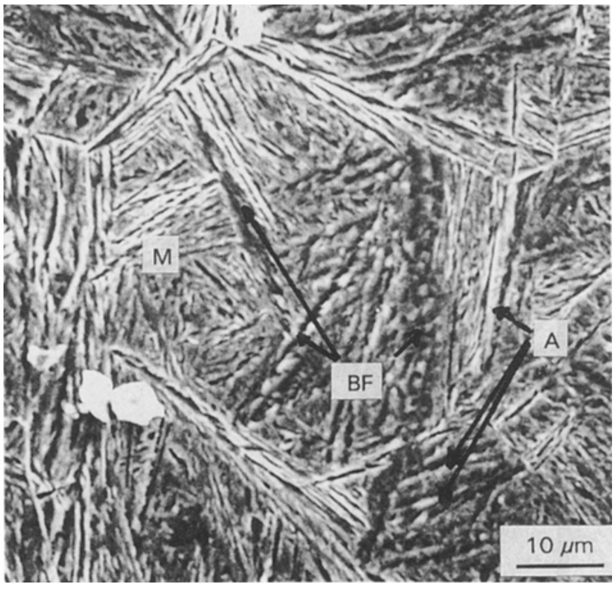

Figure 4 SEM micrograph of 60 CSM steel, IT at 673 K for 15 s. Specimen etched by 5 vol% nitrate solution. BF, A and M show bainite ferrite, retained austenite and martensite, respectively.

is produced, as silicon retards θ carbide precipitation [1–4]. Therefore the retained austenite content increased as bainitic ferrite increased. In order to clarify the formation behaviour of the retained austenite in association with the upper bainite, SEM observations were made in an early stage of bainitic transformation for 60 CSM steel. SEM revealed that the retained austenite appeared between bainitic ferrites or on surroundings of the ferrite (Fig. 4). Furthermore, TEM observation revealed that carbide precipitations occurred in the residual austenite, which was interposed between bainitic ferrites as the transformation time increased over the optimum time. Significant carbide precipitation occurred as the transformation temperature and average carbon content before bainitic transformation increased (Fig. 5). Details of the crystallographic characterization of the carbides and bainitic ferrite are described elsewhere [2–4]. This indicated that the decrease in retained austenite content beyond the optimum time was due to carbide precipitation occurring in the residual austenite and further formation of bainite ferrites beyond the optimum time.

3.2. Effect of average carbon content before bainitic transformation on retained austenite

As the formation of the retained austenite in Si–Mn

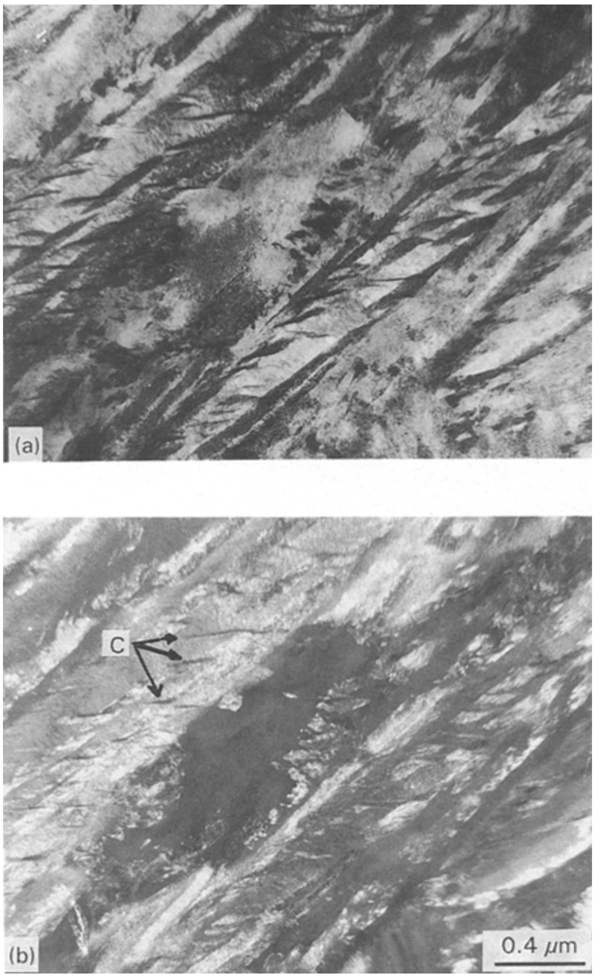

Figure 5 TEM micrograph of 75 CSM steel, IT at 673 K for 240 s. (a) Bright field; (b) dark field using $(1\,0\,0)\gamma$ austenite reflection. C shows carbide.

steel is due to carbon enrichment of the residual austenite, the retained austenite content depends on the average carbon content before bainitic transformation. In an attempt to make this clear, the effect of the average carbon content on retained austenite content was investigated using Si–Mn steels with carbon contents ranging from 0.25 to 0.75 wt %. Fig. 6 shows the effect of the average carbon content before bainitic transformation on the maximum retained austenite content of Si–Mn steels. It was found that the maximum retained austenite content increased linearly with an increase in the average carbon content.

3.3. Effect of transformation temperature on carbon content in retained austenite

The carbon content in retained austenite plays a predominant role in austenite stability. Therefore, the effect of transformation temperature on carbon content in retained austenite was investigated. The results obtained for 41 CSM, 60 CSM and 75 CSM steels are shown in Fig. 7. It was found from this result that the carbon content in retained austenite decreased with increasing temperatures from 598 to 723 K, independent of the steels. It was also found that the carbon content decreased significantly with increasing retained austenite content. Similar results have been reported elsewhere [3, 12].

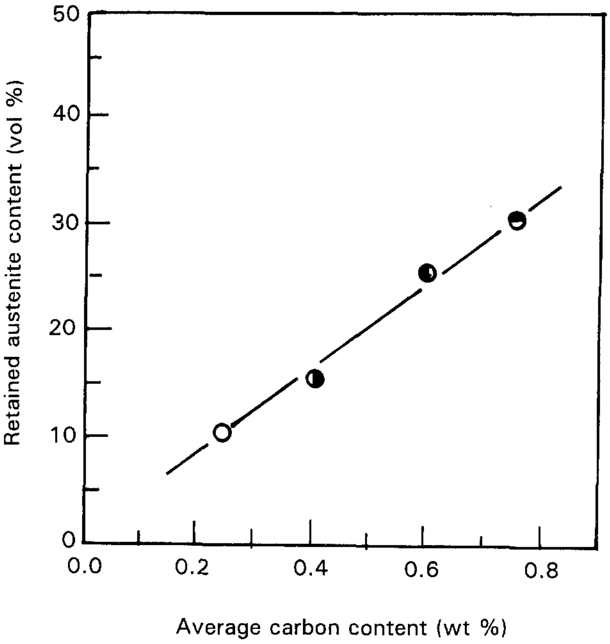

Figure 6 Effect of average carbon content before bainitic transformation on maximum retained austenite content of Si–Mn steels. Steel time ○, 25 CSM, 180 s; ◑,41 CSM, 200 s; ◐,60 CSM, 240 s; ◓,75 CSM, 600 s.

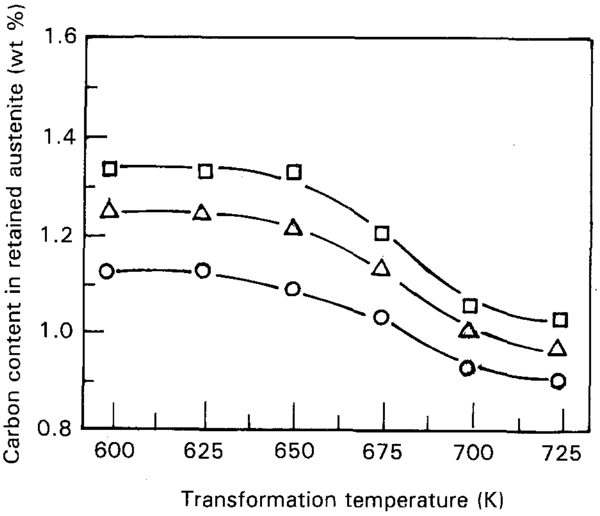

Figure 7 Effect of transformation temperature on carbon content in retained austenite of Si–Mn steels. Steel time ○, 41 CSM, 200 s; △, 60 CSM, 240 s; □, 75 CSM, 600 s.

3.4. Thermal and mechanical stability of retained austenite

The thermal and mechanical stability of the retained austenite are important for good control of the mechanical properties of bainitic-transformed steels or improved mechanical properties of the steels [5–8, 13]. Therefore the thermal and mechanical stability of retained austenite in Si–Mn steel were investigated by XRD. Fig. 8 shows the change in retained austenite content accompanying temperature

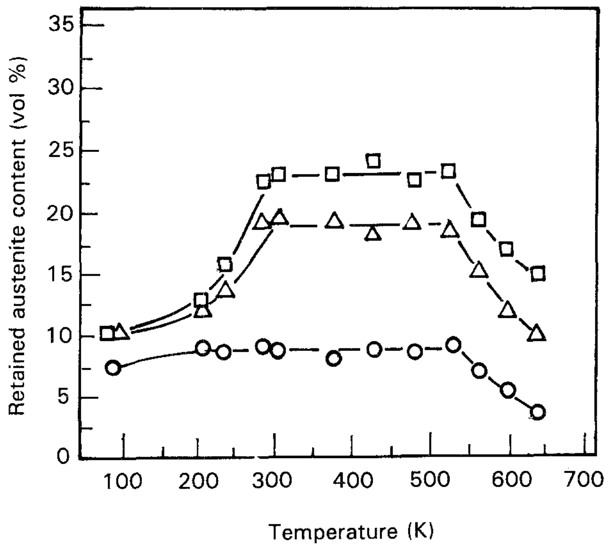

Figure 8 Change in retained austenite content accompanying temperature in 60 CSM steels. Temperature, time ○, 598 K, 400 s; △, 623 K, 300 s; □, 673 K, 240 s.

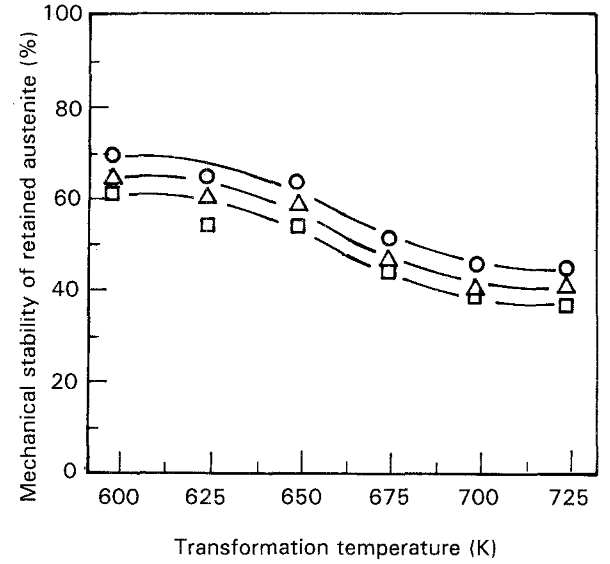

Figure 9 Effect of transformation temperature on mechanical stability of retained austenite of Si–Mn steels. Steel time ○, 41 CSM, 200 s; △, 60 CSM, 240 s; □, 75 CSM, 600 s.

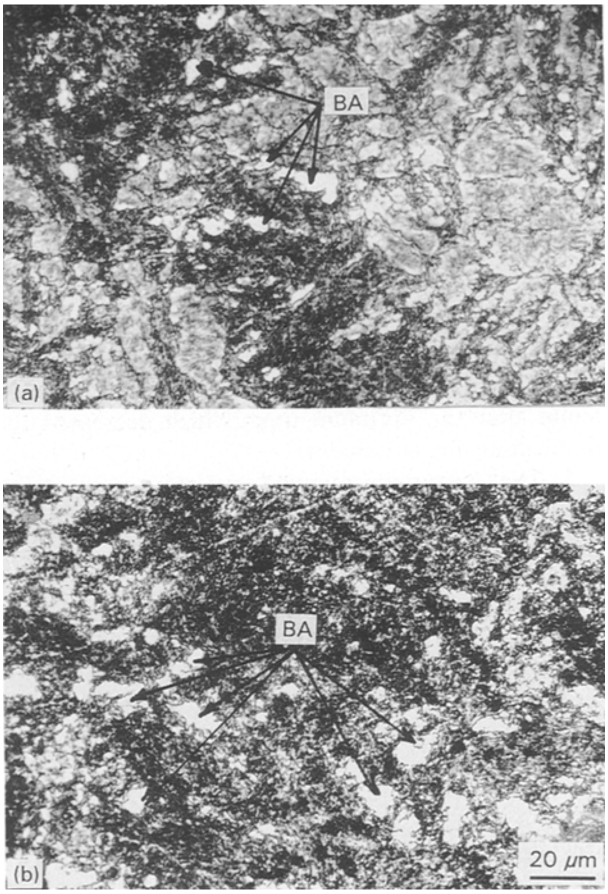

Figure 10 OM micrographs of 'blocky' type of retained austenite (BA) in IT 60 CSM steel. Specimens etched by 5 vol% nitrate alcohol solution. (a) IT at 598 K for 2500 s; (b) IT at 673 K for 180 s.

in 60 CSM steel. It was found that the decomposition temperature of retained austenite at sub-zero was higher when the transformation temperature increased, while the temperature and rate of the decomposition accompanying tempering was not dependent on the transformation temperature.

Fig. 9 shows the effect of transformation temperature on the mechanical stability of retained austenite in Si–Mn steels. The mechanical stability of the retained austenite was improved with increasing transformation temperature. The above results, together with Fig. 6, suggest that thermal and mechanical stability could be improved if the carbon content of retained austenite is increased. However, it has been reported that the mechanical stability of retained austenite is also affected by the morphology of retained austenite [7]. The effect of transformation temperature on the morphology of retained austenite was examined by OM, which revealed that the 'blocky' type of retained austenite was found, independent of transformation temperature. The average size and distribution of the blocky type were larger and heterogeneous, respectively, as transformation temperature increased [Fig. 10]. It has been reported that the blocky type of austenite has a detrimental effect on mechanical stability as it deforms in preference to bainite matrix in an early stage of plastic deformation. Therefore the morphology of retained austenite is one of the important factors which control the mechanical stability of retained austenite. However, further studies are required using many materials before quantitative conclusions can be drawn concerning the effect of the morphology of retained austenite on the mechanical stability. From the above result, it was concluded that decreasing transformation temperature is one potential approach for improving the thermal and mechanical stability of retained austenite.

4. Conclusions

1. As a result of bainitic transformation of the Si–Mn steels, the retention of a large amount of

austenite was encouraged with increasing transformation time.

2. Microstructural analysis revealed the existence of an optimum time to produce the maximum content of retained austenite.

3. The microstructure consisted of carbon-free upper bainite whose individual ferrite was separated by the 'thin-film' type of retained austenite.

4. The 'blocky' type of austenite was also found, and the size and distribution of the retained austenite were larger and more heterogeneous as the temperature increased.

4. Carbide precipitations occurred in residual austenite after the optimum time, which decreased the retained austenite content.

5. The maximum retained austenite content increased with increasing the average carbon content before bainitic transformation.

6. The carbon content in retained austenite increased with decreasing transformation temperature.

7. The thermal and mechanical stability of retained austenite were improved with decreasing transformation temperature, leading to an increased carbon content in retained austenite.

References

1. S. J. MATAS and R. F. HEHEMANN, *Trans. AIME* **221** (1961) 179.
2. H. K. D. H. BHADESHIA and D. V. EDMONDS, *Metall. Trans.* **10A** (1979) 895.
3. *Idem, Acta Metall.* **28** (1980) 1265.
4. B. P. J. SANDVIC, *Metall. Trans.* **13A** (1982) 777.
5. H. K. D. H. BHADESHIA and D. V. EDMONDS, *Met. Sci.* **17** (1983) 411.
6. *Idem, ibid.* **17** (1983) 420.
7. V. T. T. MIIHKINEN and D. V. EDMONDS, *Mater. Sci. Technol.* **3** (1987) 432.
8. *Idem, ibid.* **3** (1987) 441.
9. R. L. MILLER, *Trans. ASM* **61** (1968) 592.
10. N. RIDLEY, H. STUART, and L. ZWELL, *Trans. AIME* **245** (1961) 1834.
11. A. J. BAKER and P. M. KELLY, in "Electron Microscopy and Strength of Crystals" edited by G. THOMAS and J. WASHBURN (Interscience, New York, London, 1963) p. 899.
12. O. MATUMURA, Y. SAKUMA and H. TAKECHI, *J. Iron Steel Inst. Jpn* **77** (1991) 658.
13. S. A. KHAN and H. K. D. H. BHADESHIA, *Metall. Trans.* **21A** (1990) 859.

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