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Structure and mechanical properties of high-manganese dual-phase steels

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The structure and mechanical properties of 3 wt % Mn ferritic dual-phase steels were examined as a function of heat treatment. Because of the high maganese content, these alloys can be prepared easily even by a simple air cooling and they show a fine dispersion of martensite phase which leads to higher tensile strength and good ductility. The addition of a small amount of silicon gives beneficial effects: the tensile strength further increases without a significant loss of ductility.

1. Introduction

A lot of work was carried out over the past decade on the ferritic dual-phase steels which are, in general, low-carbon low-alloy steels consisting of two main phases: ferrite and martensite [1–10]. These steels are characterized by high tensile strength, large total elongation and low yield strength without sharp yield point, and consequently the yield strength/tensile strength ratio is small, nearly 0.4 $\sim$ 0.7. They also show very marked increases in yield strength by heating to relatively low temperatures during baking for surface coating treatment after pressing. It is now well known that the most important characteristics of these dual-phase steels are influenced by many factors such as the volume fraction of martensite phase, the deformation properties and morphology of existing phases as well as their dispersion.

In our previous work [11], we have examined the mechanical properties and fracture mechanism of Fe–0.1 wt % C–Mn dual-phase steels with a relatively small content of manganese. In those cases, rapid water-quenching from high temperature was necessary to obtain the martensite phase. The different martensite morphologies were obtained by two kinds of heat treatment used by Thomas *et al.* [7, 12]:

(a) Intercritical quenching in which the alloys were rapidly heated into the two-phase ($\alpha + \gamma$) region and then quenched to obtain the dual-phase (ferrite + martensite) structure.

(b) Double quenching which consists of two successive quenching operations. The alloys were first held for a given time in the γ-region and then quenched to obtain a uniform structure of martensite. Following this first quenching, the specimens were reheated to a lower temperature in the ($\alpha + \gamma$) region and then quenched a second time to obtain the dual-phase structure.

With a specific intention to develop a new type of dual-phase steels having a high tensile strength and a large fracture elongation, we prepared in the present work the low-carbon (less than 0.1 wt %) and high-manganese (about 3 wt %) steels and examined their microstructure and mechanical properties as a function of heat treatments. It is expected that the high manganese content presents some beneficial effects such as the mechanical reinforcement of the ferrite and the martensite phases, the decrease of the transformation temperatures, A_1 and A_3, and the facility of obtaining the martensite phase by a simple air cooling [13].

2. Experimental procedures

A number of 2 kg ingots were prepared by induction melting and cast into a water-cooled mould under an argon atmosphere. The raw materials used were: Armco iron, electrolytic manganese, the carbon being added to the molten metal in the form of about 4 wt % master alloy.

The homogenizing treatment of the cast ingots was carried out by heating at 1100° C for 20 h under an argon flow. After hot-rolling from 20 to 5.5 mm in thickness at 1100° C, the plates were cold-rolled to 5 mm, then hot-rolled again to 4 mm at 900° C and cooled in air to room temperature. Flat tensile specimens of 32 mm effective length, 6.25 mm in width and 3 mm thick were machined prior to heat treatment. The prepared specimens were tested by an Instron machine at room temperature using a 25 mm gauge length extensometer with a crosshead speed of 2 mm/min. The 0.2% offset yield strength σ_E (MPa), the ultimate tensile strength σ_R (MPa), the uniform and fracture elongation, A_u and A_R (%), were measured respectively on engineering stress–strain diagrams.

Vickers microhardness was measured on polished surfaces with a weight of 50–100 g. The microstructures were examined by the scanning electron microscope (SEM). We observed that the transformation temperatures Ac_1 and Ac_3, measured by the dilatometric method for the Fe–0.1%C–3% Mn steel were approximately 680° C and 830° C, respectively.

3. Experimental results

In the first stage of this work, we examined the

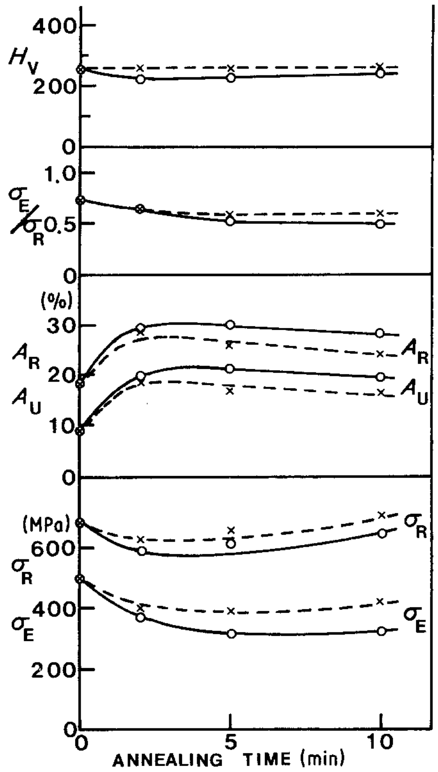


Figure 1 Results of mechanical tests on the Fe–0.06%C–2.98%Mn steels as a function of heat duration at 700° C. Full lines: air-cooled specimens, dotted lines: water-quenched specimens.

influence of the heat treatment duration at 700° C on the mechanical properties of Fe–0.06%C–2.98%Mn steels, prepared by two kinds of treatment: a simple air cooling and a water-quenching from 700° C.

In the second one, the heat treatment duration was fixed to 10 min, while the annealing temperatures were varied from 700 to 800° C. The alloy composition was Fe–0.04%C–2.88%Mn.

Finally, the effects of silicon addition to the high-maganese dual-phase steels were examined. It is expected that the silicon reduces the carbon content of ferrite, promoting the increase of ductility and strength [1, 3, 13–15].

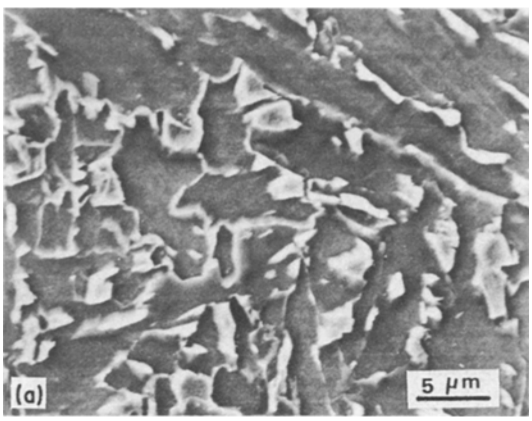
3.1. Fe–0.06%C–2.98%Mn dual-phase steels, heat-treated at 700° C

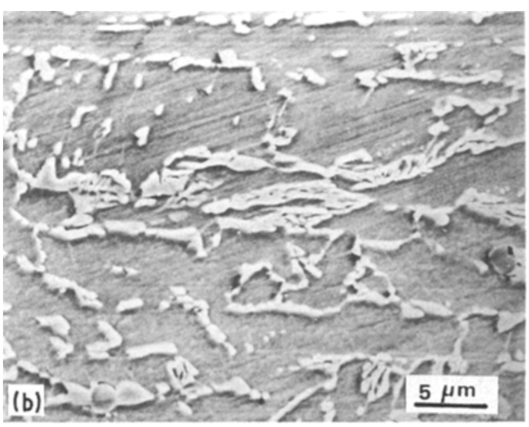
The specimens prepared by hot and cold rolling as mentioned above were heated up to 700° C and maintained at this temperature for 2, 5 or 10 min, and then one group of these specimens is cooled in air and the other quenched in water at room temperature. Fig. 1 summarizes the obtained results on the 0.2% offset yield strength σ_E, the ultimate tensile strength σ_R, the uniform- and fracture-elongation A_u and A_R, the yield strength/tensile strength ratio σ_E/σ_R and the Vickers microhardness, H_v, as a function of the annealing time at 700° C. The data with the annealing times of 0 mean those of the initial steel specimens prepared only by hot and cold rolling without a further heat treatment. The full lines correspond to the results on air-cooled specimens and the dotted lines to those of water-quenched specimens as in the cases of Figs. 3 and 5–7.

These results show that the mechanical properties do not change so much by different annealing times except a relatively small effect of softening in a first period of heat treatment at 700° C.

3.2. Structure of Fe–0.06%C–2.98%Mn alloys

Fig. 2 shows some examples of structurs observed by SEM on the above dual-phase steels. The grain size of ferrite phase is less than 10 μm. The martensite phase is mainly formed at grain boundaries of the ferrite phase with a granular or an acicular form. There is no appreciable structural difference depending on either the heat duration of 2, 5 and 10 min, or on the mode of cooling from 700° C, air cooling or water quenching. It is to be noted that the martensite phase is fairly fine and well dispersed, and that the obtained structures of these high-manganese steels are similar to





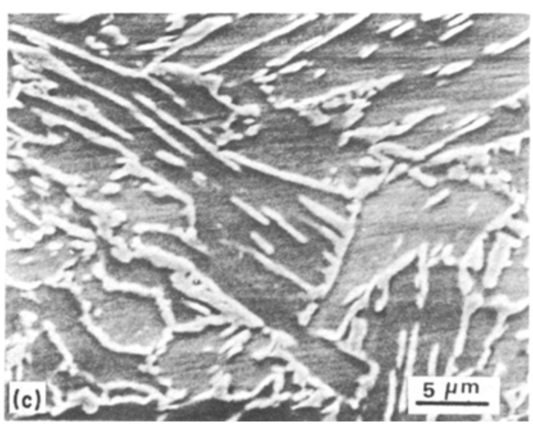


Figure 2 Structure of the Fe–0.06%C–2.98%Mn steels, observed by scanning electron microscope (SEM): (a) initial state, prepared by hot and cold rolling; (b) heated 5 min at 700° C and cooled in air; (c) heated 10 min at 700° C and quenched in water.

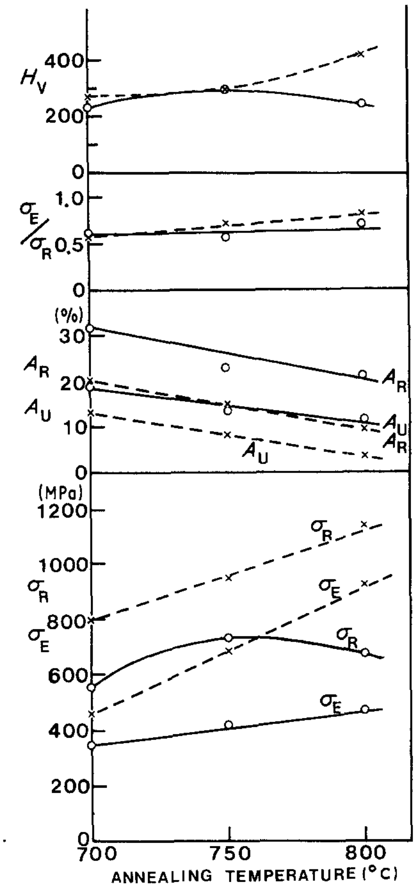


Figure 3 Results of mechanical tests on the Fe–0.04%C–2.88%Mn steels as a function of annealing temperature: 700, 750 and 800° C. Full lines: air-cooled specimens, dotted lines: water-quenched specimens.

those obtained in our previous work [11] by the double quenching of simple low-manganese steels. The mechanical properties of these new alloys are characterized by a large fracture elongation because of the fine dispersion of martensite phase and a high tensile strength which is certainly due to the high manganese content.

X-ray diffraction analysis with a goniometer recording system on the above high-manganese dual-phase steels shows the existence of a small amount of retained austenite phase but the cementite phase Fe_3C is not visible on the recording diagram of diffraction. However, the transmission electron microscopic observation shows that the cementite phase exists locally as small crystals whose length is less than $1 \sim 2\,\mu$m and breadth less than $0.5\,\mu$m.

3.3. Fe–0.04%C–2.88%Mn dual-phase steels, heat-treated at 700–800° C

The Fe–0.04%C–2.88%Mn alloys, in their initial state prepared by a simple hot and cold rolling without successive heat treatment, showed the following mean values in a tensile test: $\sigma_E = 494$ MPa, $\sigma_R = 638$ MPa, $A_u = 8.0\%$ and $A_R = 15.0\%$. These results are nearly similar to those obtained in the previous section.

Then, these alloys were heated for a fixed duration, 10 min, at various temperatures: 700, 750 and 800° C, respectively. And, one group of them was cooled in air, and the other quenched in water at room temperature. Fig. 3 summarizes the results of mechanical

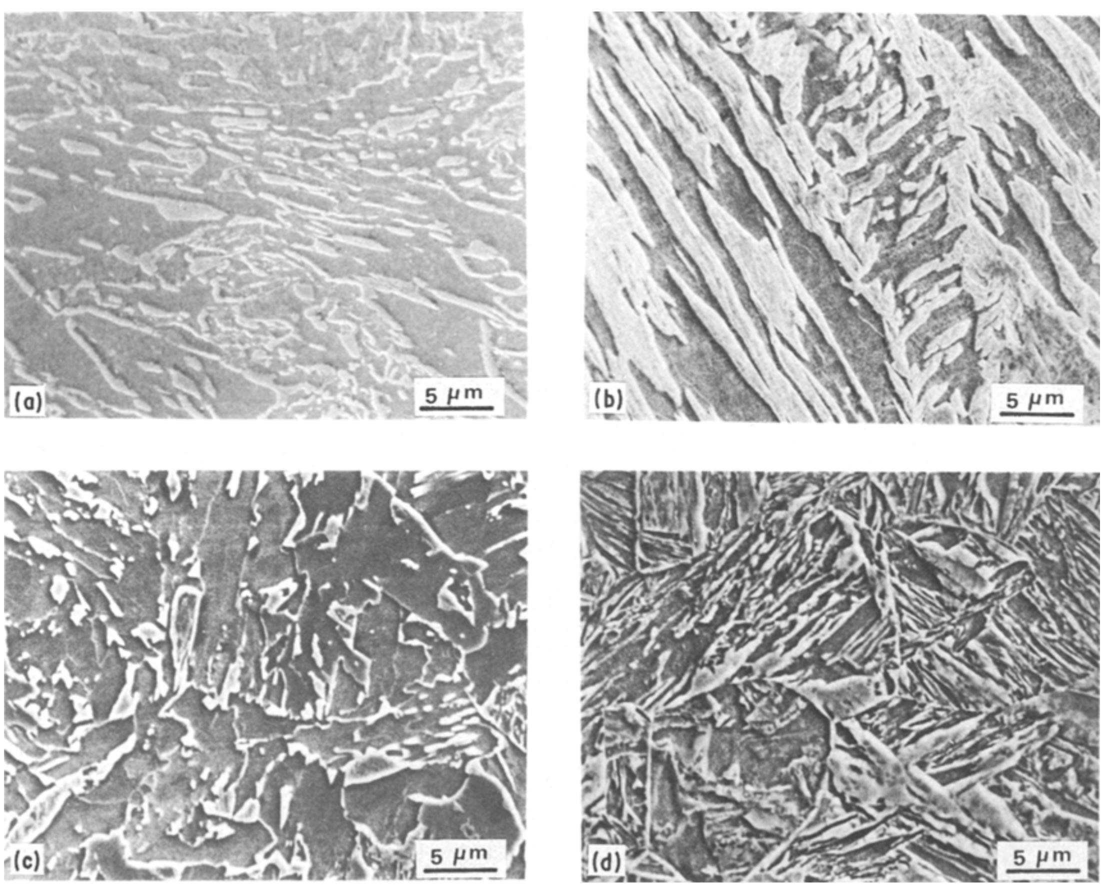


Figure 4 Structure of the Fe–0.04%C–2.88%Mn steels, observed by SEM: (a) heated at 750° C and cooled in air; (b) heated at 750° C and quenched in water; (c) heated at 800° C and cooled in air; (d) heated at 800° C and quenched in water.

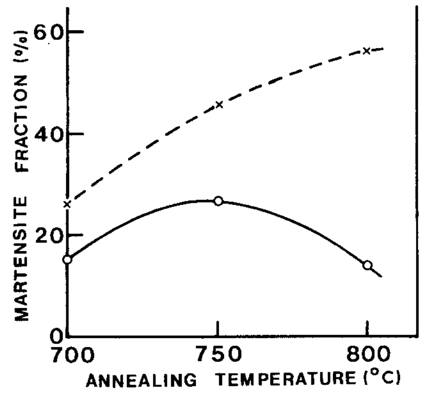


Figure 5 Martensite volume fraction as a function of annealing temperature. Full lines: air-cooled specimens, dotted lines: water-quenched specimens.

tests on these two groups of steels as a function of annealing temperature.

Fig. 4 shows the structure of the above steels, prepared by heat treatment at 750 and 800° C. The morphology of the martensite phase largely varies according to the annealing temperature and the mode of cooling from high temperature. The variation of the martensite volume fraction, measured by a line intersection method on SEM micrographs, is shown in Fig. 5 as a function of annealing temperature. The amount of martensite phase increases as the heating temperature increases for the water quenched specimens, while it attains a maximum value at about 750° C and then decreases at higher temperatures for the air-cooled specimens. This variation behaviour is easily understandable from the cooling velocity and the isothermal transformation curve of steels.

The general aspect of mechanical properties shown in Fig. 3 is also in good agreement with this variation of martensite volume fraction. The tensile strength increases linearly as the annealing temperature increases for the water-quenched steels, while it attains the maximum value by heat treatment at 750° C and then decreases by higher annealing temperature. It may be possible that there is a slightly larger amount of cementite in the air-cooled specimens from 800° C such as that shown in Fig. 4c, even though its amount is still so small that X-ray diffraction shows no trace of this phase.

3.4. Effects of silicon addition

We further prepared the following four kinds of steels in order to examine the influence of silicon addition on the mechanical properties of the high-manganese dual-phase steels.

1. Fe–0.04%C–2.88%Mn–0.22%Si.
2. Fe–0.025%C–2.94%Mn–0.52%Si.
3. Fe–0.04%C–2.91%Mn–0.96%Si.
4. Fe–0.05%C–2.80%Mn–1.13%Si.

These alloys were heat-treated as in the previous case of the Fe–0.04%C–2.88%Mn alloys. They were held during 10 min at 700, 750 or 800° C, respectively, and then cooled in air or quenched in water at room temperature.

Fig. 6 summarizes the results of mechanical tests for each kind of these alloys, which should be compared with those of Fig. 3 for the silicon-free steels.

We plotted the obtained results of mechanical tests, neglecting the small difference of carbon and manganese contents, as a function of silicon content for three different annealing temperatures as shown in Fig. 7. The obtained results show that the silicon addition increases remarkably the mechanical strength. This effect is especially significant up to 0.5% silicon. For example, we obtained the tensile strength of about 800 MPa with 20% fracture elongation by a simple air cooling from 700° C for the alloy containing 0.5% Si. These values are modified to be more than 1000 MPa for tensile strength and 15% total elongation by air cooling from 750° C. The fracture elongation decreases by the silicon addition but it still retains a relatively high value.

4. Concluding remarks

The mechanical properties of the ferrito–martensite dual-phase steels depend first on the volume fraction of the martensite phase and secondly on the dispersion of this hard phase in a ferritic matrix. The third factor is the mechanical properties of the ferrite and the martensite phases themselves depending on the dissolved elements. The presence of the retained austenite seems favourably to increase the fracture elongation by the mechanism of transformation induced plasticity [9].

Our experimental results show that the addition of high manganese content to low carbon steels presents the following beneficial influences for the formation of high strength ductile ferritic dual-phase steels:

(a) The transformation temperatures A_1 and A_3 decrease and the TTT-curve is displaced towards the right side. This facilitates the preparation of the dual-phase steels by a simple cooling even in air from a relatively low temperature.

(b) The addition of high manganese content gives a much finer dispersion of the martensite phase in the ferrite matrix. This increases the tensile strength and the fracture elongation. The retained austenite may be obtained more easily by the manganese addition, which probably contributes to the increase of the ductility.

(c) The high manganese content increases the strength of the ferrite and the martensite phases by the solid-solution hardening.

The alloys near the composition Fe–0.05% C–3%Mn produce a tensile strength of 600 MPa with more than 30% fracture elongation by air cooling from 700° C. It is possible to control the martensite volume fraction within a large range by annealing temperatures and cooling conditions.

In the case of air cooling, the amount of martensite phase attains its maximum value (27%) by heat treatment at 750° C and we obtained the tensile strength of about 730 MPa with the total elongation 23%. The air cooling from a higher temperature than 750° C decreases the amount of martensite phase and consequently the tensile strength also decreases. Water quenching, however, increases the martensite volume

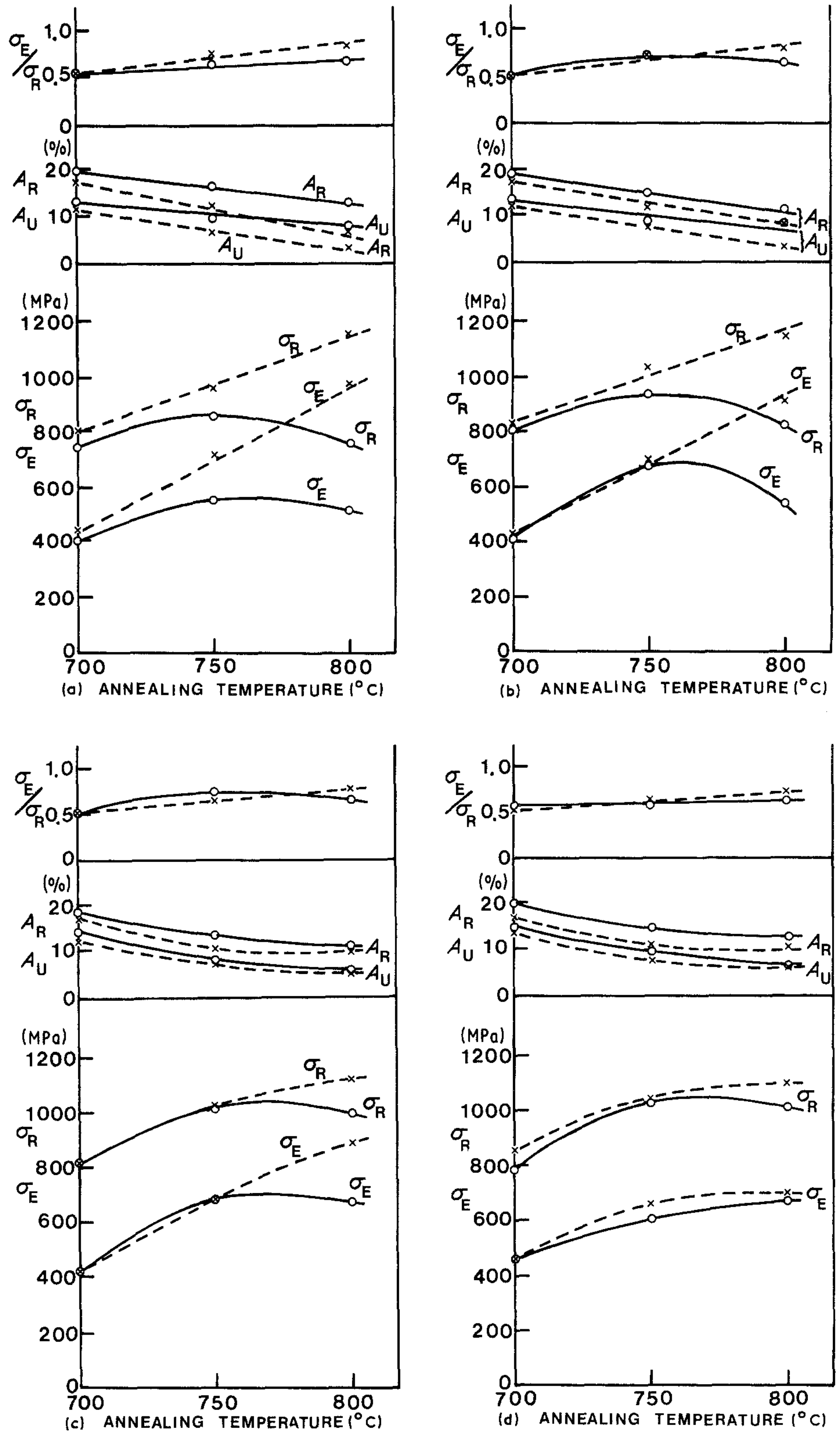
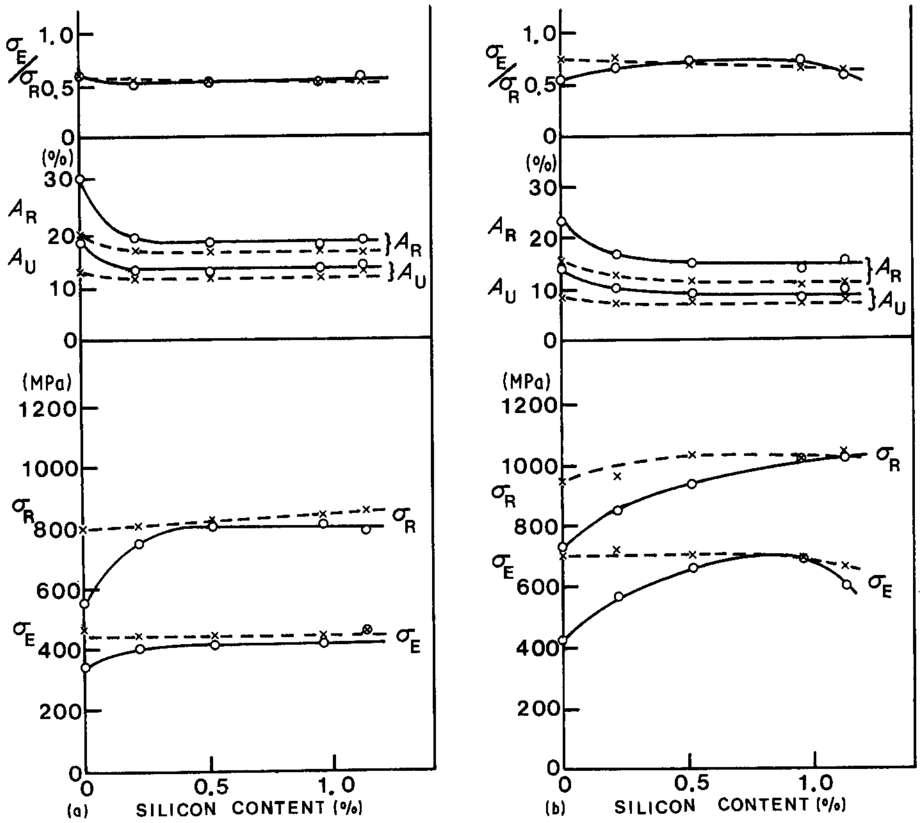


Figure 6 Results of mechanical tests on the silicon-containing high-manganese dual-phase steels: (a) Fe–0.04%C–2.88%Mn–0.22%Si; (b) Fe–0.025%C–2.94%Mn–0.52%Si; (c) Fe–0.04%C–2.91%Mn–0.96%Si; (d) Fe–0.05%C–2.80%Mn–1.13%Si. Full lines: air-cooled specimens, dotted lines: water-quenched specimens.

fraction as the annealing temperature increases. We obtained the tensile strength of 950 MPa with the fracture elongation of about 15% by water quenching from 750° C and the tensile strength of 1140 MPa with the total elongation near 10% by water quenching from 800° C. The results show that the high-manganese dual-phase steels present very good mechanical properties, high strength and high ductility, even though their chemical composition is still very simple.

The promising mechanical properties are further improved by the addition of a small amount of silicon. The tensile strength increases without a significant loss of ductility and it is possible to realize the tensile strength of 800 MPa with 20% fracture elongation and the tensile strength of more than 1000 MPa with about 15% total elongation by a simple air cooling from 700° C and 750° C, respectively.



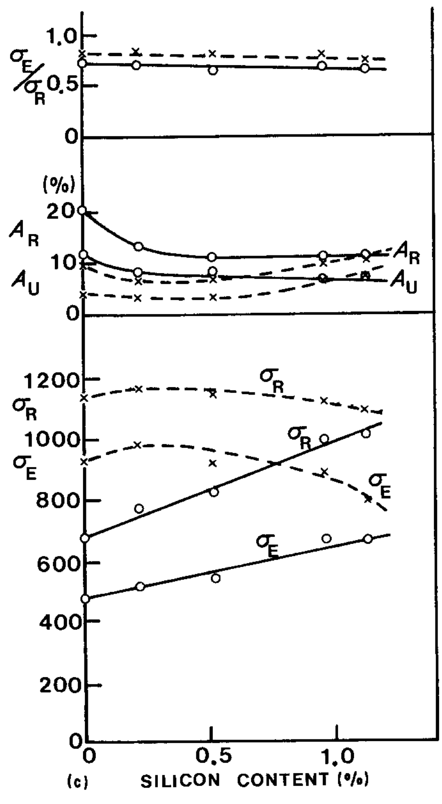


Figure 7 Effects of silicon addition on the mechanical properties of high-manganese dual-phase steels. Specimens were held during 10 min at temperatures: (a) 700° C, (b) 750° C and (c) 800° C, respectively. Full lines: air cooled specimens, dotted lines: water-quenched specimens.

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References

1. S. HAYAMI and T. FURUKAWA, Micro Alloying 75, Proceeding of a Symposium on High Strength, Low-Alloy Steels, Products and Process (Union Carbide Corp., New York, 1975) p. 78.
2. T. MATSUOKA and K. YAMAMORI, *Met. Trans.* **6A** (1975) 1613.
3. K. ARAKI, S. FUKUNAKA and K. UCHIDA, *Trans. Iron Steel Inst. Jpn* **17** (1979) 701.
4. A. T. DAVENPORT (Ed.), "Formable HSLA and Dual-Phase Steels" (The Metal Society AIME, New York, 1979).
5. R. A. KOT and J. W. MORRIS, (Eds), "Structure and Properties of Dual-Phase Steels". (The Metal Society AIME, New York, 1979).
6. W. S. OWEN, *Met. Technol.* **7** January (1980) 1.
7. N. J. KIM and G. THOMAS, *Met. Trans.* **12A** (1981) 483.
8. G. R. SPEICH, V. A. DEMAREST and R. L. MILLER, *Met. Trans.* **12A** (1981) 1419.
9. T. FURUKAWA, H. MORIKAWA, M. ENDO, H. TAKECHI, K. KOYAMA, O. AKISUE and T. YAMADA, *Trans. Iron Steel Int. Jpn.* **21** (1981) 812.
10. T. FURUKAWA, M. TANINO, H. MORIKAWA and M. ENDO, *ibid.* **24** (1984) 113.
11. X. -J. HE, N. TERAO and A. BERGHEZAN, *Met. Sci.* **18** (1984) 367.
12. G. THOMAS and J. Y. KOO, "Structure and Properties of Dual-Phase Steels" edited by R. A Kot and J. W. Morris (The Metal Society AIME, New York, 1979) p. 183.
13. E. C. BAIN and H. W. PAXTON, "Alloying Elements in Steel" (American Society for Metals, Ohio, 1966) Chap. 4.
14. J. Y. KOO and G. THOMAS, *Met. Trans.* **8A** (1977) 525.
15. R. G. DAVIES, *ibid.* **10A** (1979) 113.

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