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Effects of Ni and Mn on brittle-to-ductile transition in ultralow-carbon steels

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A R T I C L E I N F O

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A B S T R A C T

The temperature dependence of the effective stress indicated that both Ni and Mn induce solid solution softening at low temperatures. The activation energy for dislocation glide was obtained from the temperature dependence of the activation volume and effective shear stress. Either Ni or Mn decreases the activation energy for dislocation glide, which suggests that both Ni and Mn decrease the brittle-to-ductile transition (BDT) temperature. However, the temperature dependence of the absorbed energy for fracture showed that the transition temperature decreases with Ni but increases with Mn. Fracture surfaces tested at 100 K indicated transgranular fracture at 2 mass% Ni and intergranular fracture at 2 mass% Mn, which suggests a decrease in energy for grain boundary fracture with Mn. The mechanism behind the opposite effects of Ni and Mn on the transition temperature of ultralow-carbon steels was examined on the basis of dislocation shielding theory.

1. Introduction

Manganese (Mn) is an important element added in steel that reduces the grain size and increases the yield stress at room temperature (RT). It also influences the stability of austenite, decreasing a martensite-start temperature. Mechanical properties of transformation-induced plasticity-aided steels are influenced by the Mn, which is mainly due to the change in microstructures with Mn [1–3]. In case of ferrite single phase steels, Mn and nickel (Ni) show similar effects on the mechanical properties. Okazaki, Uenish and Teodosiu [4,5] reported the temperature dependence of the yield stresses for titanium-added Fe–1 at% Ni and Fe–1 at% Mn, which showed solid solution hardening at RT and solid solution softening at low temperatures or high-strain rates. The solid solution softening suggests that Ni and Mn increase the dislocation velocity at low temperatures. Maeno et al. [6] reported that the decrease in the brittle-to-ductile transition (BDT) temperature with increasing Ni in steel can be explained by the increased dislocation velocity at low temperatures. This suggests that increasing the Mn content decreases the BDT temperature. However, the effect of Mn on toughness is still controversial. For instance, Jolley [7] reported that the BDT temperature of furnace-cooled ferrite with a single phase increases with up to 1.8 mass% Mn, while the BDT temperature of ferrite with cementite decreases with Mn. Yamanaka and Kobayashi [8] reported a complex trend for the BDT temperature with Mn. The BDT temperature decreases with increasing Mn to a minimum at 2 mass% Mn and then increases with higher Mn content. They investigated the microstructure and pointed out that the microstructure depends on the Mn content; uniaxial ferrite and massive ferrite are dominant with low Mn content and 3 mass% Mn, respectively. Specimens with a Mn content of 4.8 mass% exhibit lath martensite in massive ferrites. Mn has complicated effects on the microstructure, which include grain refinement, micro-segregation, and changes to the morphology of precipitates. Mn produces many effects, which makes it difficult to understand the specific effect of Mn on the fracture toughness and BDT.

In the present study, therefore, the effects of Mn and Ni as solute atoms on BDT were clarified by using single-phase ferrites with different concentrations of Mn and Ni but nearly the same grain sizes. The mechanism behind the changes in the BDT temperature with Mn and Ni was examined on the basis of dislocation shielding theory [9].

2. Experimental procedure

Table 1 presents the chemical compositions of the materials employed in this study. The base material was ultralow-carbon steel with a C concentration of less than 20 ppm. For the specimens, 1 or 2

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Table 1
Chemical compositions of the employed materials.

	C	Si	Mn	P	S	Ni	Ti	Al	N
0Mn	0.0017	< 0.01	< 0.01	< 0.01	< 0.001	< 0.01	< 0.002	0.03	< 0.001
1Mn	0.0018	< 0.01	0.97	< 0.01	< 0.001	< 0.01	< 0.002	0.03	< 0.001
2Mn	0.0018	< 0.01	1.95	< 0.01	< 0.001	< 0.01	< 0.002	0.03	< 0.001
1Ni	0.0019	< 0.01	< 0.01	< 0.01	< 0.001	1.01	< 0.002	0.03	< 0.001
2Ni	0.0019	< 0.01	< 0.01	< 0.01	< 0.001	2.02	< 0.002	0.03	< 0.001

mass% of Ni or Mn was added to the base material and labelled as 0Mn, 1Mn, 2Mn, 1Ni, and 2Ni. The grain sizes of 0Mn, 1Mn, 2Mn 1Ni and 2Ni were measured to be 147, 91, 59, 86, and 78 µm, respectively.

The parallel portion and width of the tensile specimens were 8 and 2 mm, respectively, and they had a thickness of 0.9 mm. Strain gages were attached to the parallel portions of the specimens. The test temperature was varied between 77 and 350 K. The initial strain rate of the tensile tests was set to 4.2×10^{-4} s^{-1}, and a Shimadzu AG-IS was used for the tests. Strain-rate jump tests were performed in order to obtain the activation volume. The strain rate was jumped by one order of magnitude. The impact fracture energy of the specimens was measured by using an instrumental impact fracture machine (Tanaka MIT-D05KJ). The blade speed of the impact tests was set to be 3.3×10^{-1} ms^{-1}.

3. Results

Fig. 1 shows the nominal stress–strain curves of 1Ni, 2Ni, 0Mn, 1Mn, and 2Mn measured at 77 K and RT. Yield drop was observed at RT for all specimens. At RT, the yield stress of 0 M is the lowest, that of 2Ni was higher than that of 1Ni, and the yield stress of 2Mn was higher than that of 1Mn. These results demonstrate solid solution hardening. On the other hand, at 77 K, the yield stress of 2Ni was lower than that of 1Ni, and the yield stress of 2Mn was lower than that of 1Mn. This indicates that both Ni and Mn induce solid solution softening at 77 K. The temperature dependence of the yield stress was obtained next. Because these materials were low-carbon steels, some specimens showed yield drop, thus, 0.2% proof stress was taken as the yield stress for the specimens that showed continuous yielding while the lower-yield point was taken as the yield stress for those showed the yield drop.

Fig. 2 shows the temperature dependence of the yield stress for 1Ni, 2Ni, 0Mn, 1Mn, and 2Mn. The yield stress decreased with increasing temperature; the temperature dependence then a nearly negligible above 300 K. The trend is the same as that typically seen in bcc crystals. It is worth pointing here that slight hump is also seen in between 125 K and 225 K in polycrystalline 0Mn. It is much significant reported in single crystalline iron [10]. The normal temperature dependence of the yield stress originates from the process that dislocations overcoming short-range barriers through a thermally activated process. In bcc crystals, the dominant thermally activated process for dislocation glide at low temperatures is overcoming the Peierls barrier. Therefore, temperature dependence of yield stress will be investigated next.

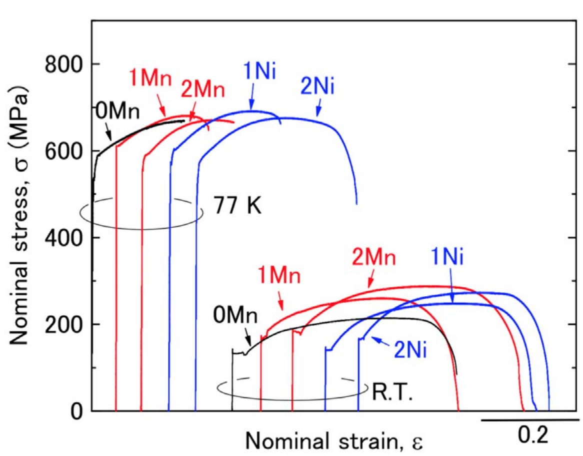

Fig. 1. Nominal stress–strain curves from 1Ni, 2Ni, 0Mn, 1Mn, and 2Mn tested at 77 K and RT.

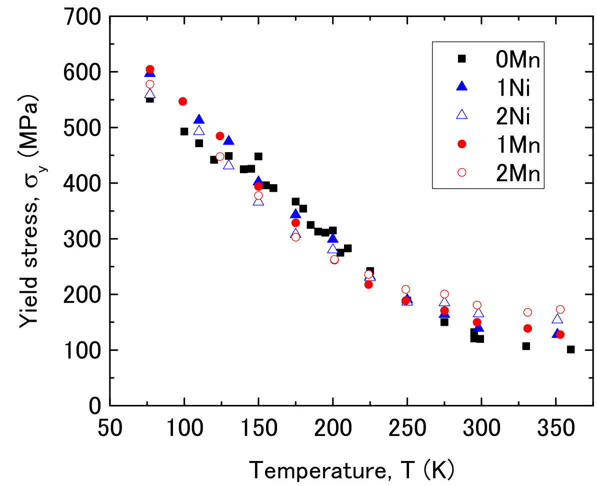

Fig. 2. Temperature dependence of the yield stress.

The yield stress can be expressed as follows:

$$\sigma_y = \sigma_e + \sigma_{ath}, \quad (1)$$

where σ_e and σ_{ath} are the effective stress and athermal stress, respectively. The effective stress and athermal stress are temperature-dependent and temperature-independent, respectively. In the present study, the yield stress at 350 K was defined as the athermal stress. Fig. 3 shows the temperature dependence of the measured effective stresses for 1Ni, 2Ni, 0M, 1Mn, and 2Mn according to Eq. (1). The effective stress decreased with increasing Ni or Mn content, which indicates that the solid solution softening at low temperatures in Fig. 2

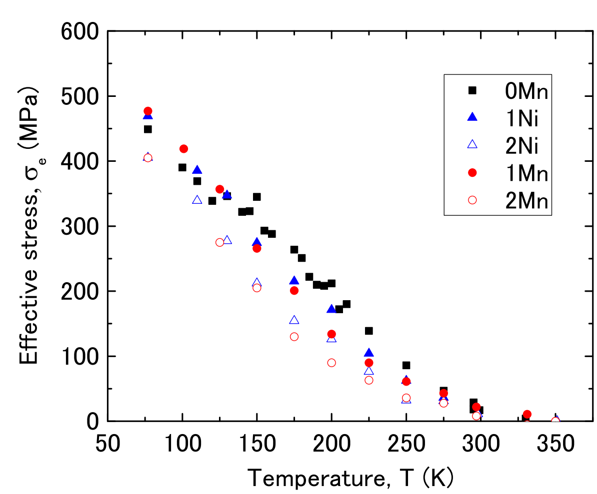

Fig. 3. Temperature dependence of the effective stress.