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DOI: 10.1017/S1431927606061071
Microsc Microanal 12(Supp 2), 2006

Transmission Electron Microscopy Study of 2400 MPa Grade Co-free Maraging Steels

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Abstract

The age hardening kinetics in the temperature range of 713-813 K of two 2400 MPa grade Co-free maraging steels (Fe-19.1%Ni-4.4%Mo-2.63%Ti, 1#, and Fe-18.8%Ni-5.39%Mo-2.59%Ti, 2#, wt. %) has been studied. Study of microstructure and mechanical properties showed that a high number of Ni_3Ti and $Fe_2(Mo,Ti)$ precipitates were formed during the ageing process, which resulted in high strength and relatively low fracture toughness. Ni_3Ti was the main precipitation phase. Fractography has shown ductile failure of tensile and fracture toughness specimens. Thermodynamic calculations showed that the equilibrium phases are Ni_3Ti, $Fe_2(Mo,Ti)$, ferrite and austenite.

Microstructure

Figs. 1a and 1b show the typical microstructure for steel 1# and steel 2#, respectively. From transmission electron microscopy (TEM) experiments, it was found that the two steels have the same microstructural characteristics in the peak-ageing condition (753K/3h) after solution treatment at 1083 K for 1 hour. The microstructure of both steels consists of martensite lath with many coarse precipitates along lath boundaries (Fig. 1a) or in the lath matrix randomly (Fig. 1b). The mean diameter of these coarse precipitates is about 120 nm. The TEM bright field image of Fig. 2 clearly shows the extremely densely distributed needle-shape precipitates, dislocations as well as dislocation tangles in the martensite matrix. Fig. 3 is a TEM dark field image and selected area diffraction (SAD) pattern for steel 1#. It can be identified that the needle-shape precipitates are Ni_3Ti using the $(01\bar{1}1)_{Ni3Ti}$ diffraction spot (indicated with an arrow in Fig. 3b). The average diameter and length of the precipitates are about 4 nm and 15 nm, respectively, as shown in Fig. 3a. In both of the steels, these extremely dense nanometre-size Ni_3Ti precipitates uniformly distribute in the martensite matrix with certain crystallographic orientation, and play dominating strengthening role by pinning the movement of dislocations.

Besides the overwhelmingly populated nanometre-size Ni_3Ti precipitates in the martensite matrix of both steels, a high number of coarse phases with mean diameter of 120 nm are randomly distributed in matrix (Fig. 1). This kind of coarse phase is much larger than Ni_3Ti precipitates, and there is no coherency or crystallographic orientation relationship with the matrix. This type of coarse phase might be Fe_2Mo intermetallic phase mixed with Ti element, and herein it is denoted as $Fe_2(Mo,Ti)$. The coarse phases in both steel have been confirmed by thermodynamic calculations. In TEM observations, no signs of residual austenite or reverted austenite are visible in the peak-ageing condition for the two steels.

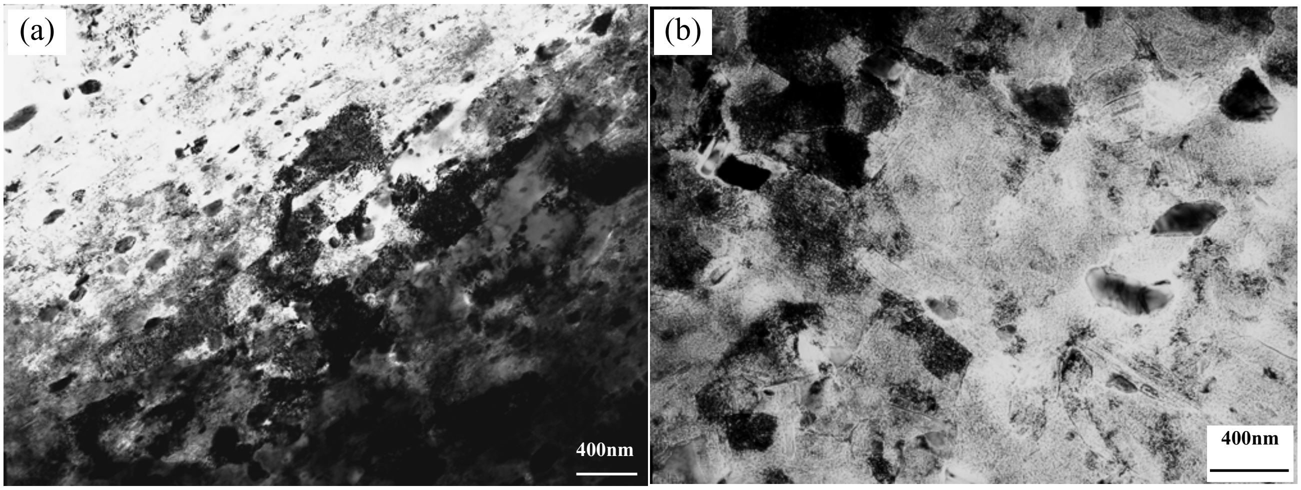

Fig. 1. TEM bright field images of martensite matrix and coarse phase for steel 1# (a), and for steel 2# (b).

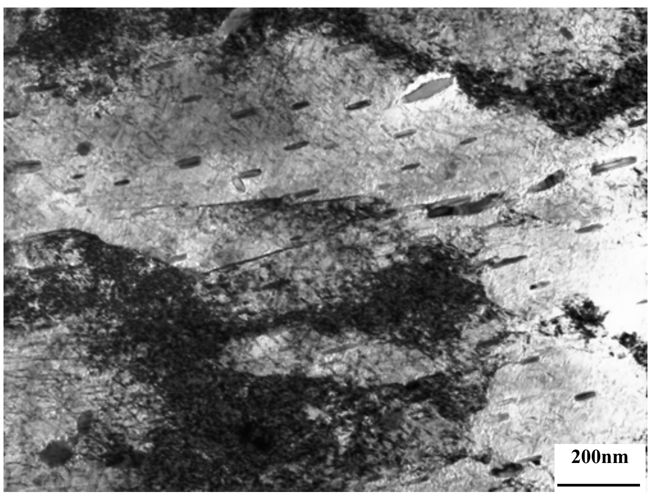

Fig. 2. TEM bright field image of microstructure for steel 1#, showing high densities of dislocations and precipitates, and coarse phase in martensite matrix.

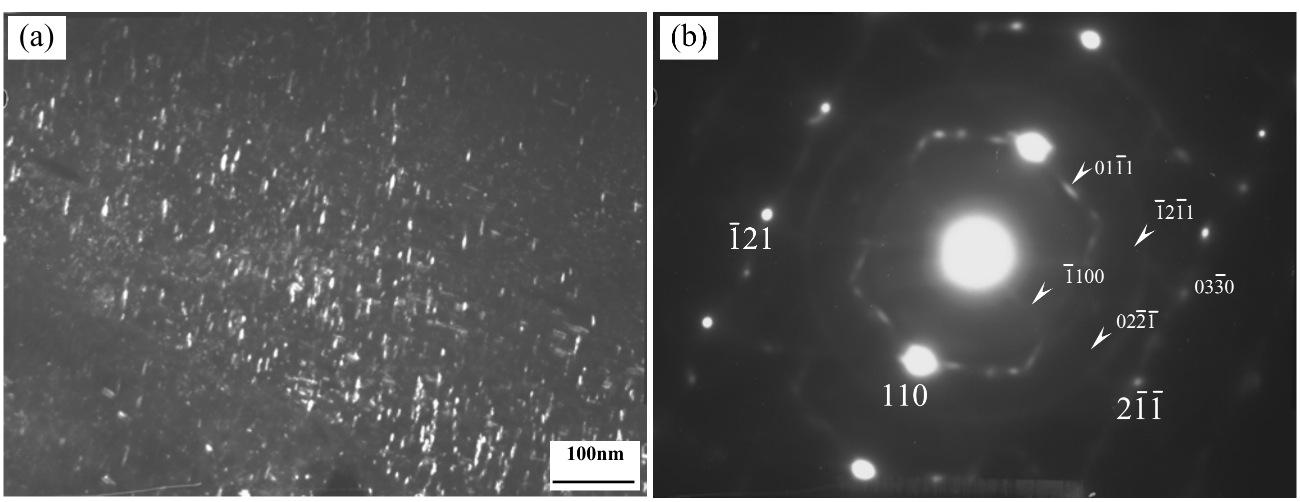

Fig. 3. TEM dark field image and SAD pattern for steel 1#. (a) Dark field image, showing high density of Ni_3Ti precipitates taken from the $(01\bar{1}1)_{Ni3Ti}$ spot indicated in (b); (b) $[\bar{1}1\bar{3}]_M$ SAD pattern.