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Effect of further alloying on the microstructure and mechanical properties of an Fe–10Ni–5Mn maraging steel

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Abstract

An Fe–10Ni–5Mn (wt.%) maraging steel was further alloyed with higher amounts of molybdenum, titanium, chromium and tungsten additions. Optical, scanning and transmission electron microscopy, X-ray diffraction and tensile test were used to study effect of the further alloying on the microstructure and mechanical properties of the present steel. Austenite retention was found as a consequence of further alloying. The retained austenite showed mechanical instability and transformed to martensite during tensile deformation, giving rise to high uniform tensile elongation. Precipitation of a molybdenum-enriched second phase particle was identified at austenite grain boundaries presumably due to excess alloying elements content.

Keywords: Maraging steel; Alloying; Austenite retention; Grain boundary; Precipitation

1. Introduction

Maraging steels are a group of ultrahigh strength steels possessing good fracture toughness. Many applications of maraging steels in aerospace, military and production tooling have been realized due to their unique combination of superior mechanical properties, suitable weldability and simple heat treatment [1]. However, maraging steels are highly cost in part because of expensive alloying contents like nickel and cobalt. Extensive researches have been carried out on the development of low-cost maraging steels through substitution of nickel and cobalt by cheaper elements like manganese, chromium, etc. For example, cobalt-free 18Ni maraging steels were developed in early 1980s [2]. A promising maraging characteristic has also been found in Fe–Ni–Mn steels [3].

Age hardening of Fe–Ni–Mn maraging steels is attributed to the precipitation of fct θ-NiMn intermetallic compound at lath martensite [4,5]. However, reversion to fcc austenite has been found in these steels during isothermal aging which decreases their hardness at later stages of aging [6,7]. Fe–Ni–Mn maraging steels suffer from premature intergranular fracture along prior austenite grain boundaries after aging [8,9]. Analogous to the deleterious effect of manganese segregation in grain boundary embrittlement of Fe–Mn [10,11] and temper embrittlement of low alloy steels [12], early studies suggested that segregation of manganese atoms at prior austenite grain boundaries during isothermal aging is responsible for the grain boundary embrittlement of Fe–Ni–Mn maraging steels [8,13]. However, it later turned out that pronounced grain boundary precipitation causes intergranular brittleness in these steels. For example, Mun et al. [14] first reported precipitation of fcc reverted austenite particles at grain boundaries in an Fe–8Mn–7Ni (wt.%) maraging steel. Then, Lee et al. [15] found precipitation of fct θ-NiMn intermetallic compound at grain boundaries of an Fe–10Ni–5Mn (wt.%) steel. Wilson [16] criticized that manganese segregates at grain boundaries as an initial step in the formation of grain boundary precipitates and acts as a major embrittling element in the early stages of aging. Recently, Hossein Nedjad [17] identified discontinuous coarsening of fct θ-NiMn precipitates at grain boundaries during isothermal aging of an Fe–10Ni–7Mn (wt.%) maraging steel. A new mechanism for grain boundary fracture of the Fe–Ni–Mn maraging steel is to be published elsewhere.

Effect of further alloying on the grain boundary brittleness of Fe–Ni–Mn maraging steels has been investigated extensively [18–22]. Among those alloys, an Fe–9Ni–5Mn–5Mo (wt.%) steel showed improved tensile properties [20]. By further

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alloying, more improvement in tensile properties was then found in an Fe–9Ni–5Mn–5Mo–1.5Ti–3Cr (wt.%) maraging steel [23]. Later, by further chromium addition, ductile grain boundary fracture with moderate tensile strength but poor tensile elongation was reported in an Fe–9Ni–5Mn–5Mo–1.5Ti–3.8Cr (wt.%) maraging steel as a consequence of pronounced grain boundary precipitation [24]. Meanwhile, austenite can be retained when those steels contain higher amounts of alloying elements like Ni, Mn, Mo, etc. [25]. The retained austenite in maraging steels is mechanically unstable at room temperature and transforms to martensite upon straining giving rise to transformation-induced plasticity (TRIP) [26–28].

This paper is aimed to continue further alloying of Fe–Ni–Mn–Mo–Cr–Ti maraging steel. Effect of further alloying on the microstructure and mechanical properties has been investigated.

2. Experimental procedure

An Fe–10.57Ni–4.95Mn–5.86Mo–4.45Cr–1.43Ti–0.55W (wt.%) maraging steel with 0.020C–0.136Si–0.008S–0.001P–0.052Al (wt.%) was prepared in a vacuum arc melting furnace using electrolytic iron, manganese, chromium, pure nickel shots, pure tungsten rods, ferromolybdenum and ferrotitanium brickets. A homogenization treatment was performed at 1523 K for 10.8 ks followed by hot forging at 1250–1400 K. Hot rolling was carried out at 1100–1300 K for 50% followed by water quenching. Half-size tensile test pieces were cut from the hot rolled strips according to ASTM E-8. Tensile tests were carried out by an Instron universal tensile test machine at a crosshead speed of 0.5 mm/min. Annealing treatments at 1098 K were performed in a vacuum furnace operating at 10^{-3} Torr. X-ray measurements were carried out using Cu Kα radiation of 40 kV and 35 mA in a Bruker D8 diffractometer with a step size of 0.02° scanned at 1 s. For optical and scanning electron microscopy, mechanically polished specimens were chemically etched in the Kalling's reagent (33 ml HCl, 33 ml ethanol, 33 ml distilled water and 5.1 g $CuCl_2$). Transmission electron microscopy of electropolished thin foils was carried out using a PHILIPS CM200-FEG microscope operating at 200 kV.

3. Results

Fig. 1 illustrates the engineering stress–strain curve of the hot rolled steel, manifesting high uniform tensile elongation along with a moderate tensile strength. Fig. 2 (a) shows an optical micrograph of the hot rolled steel indicating pancake grains elongated in the rolling direction. Fig. 2(b) shows substructures developed homogenously within the pancake grains after tensile deformation, resembling the substructure of lath martensite in maraging steels. Fig. 3 (a) and (b) shows transmission electron micrographs obtained from the hot rolled and tensile deformed steels, respectively. In the hot rolled steel, a dislocated austenitic microstructure is demonstrated which transformed to martensite during tensile deformation. X-ray diffraction spectra obtained from the hot rolled and deformed steels are shown in Fig. 4 (a) and (b), respectively. The hot rolled steel show fcc austenite peaks which could retain even after dipping in liquid nitrogen for 3.6 ks. However, in the deformed steel, both fcc austenite and bcc martensite peaks are demonstrated. Fig. 5 (a) shows a scanning electron micrograph of grain boundary precipitates in the hot rolled steel. An energy dispersive X-ray spectrum

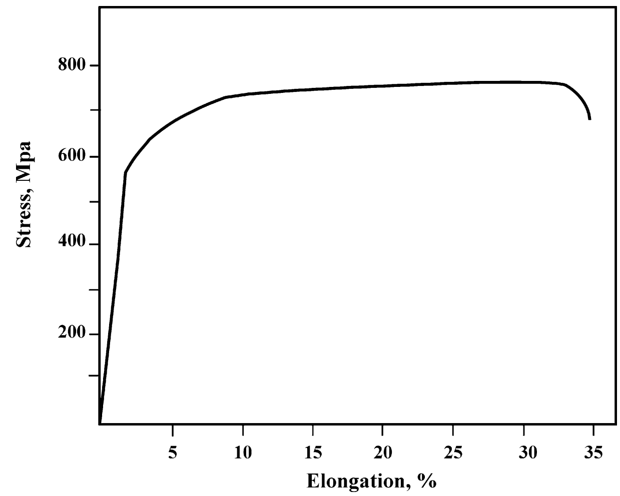

Fig. 1. The engineering stress–strain curve of the hot rolled steel.

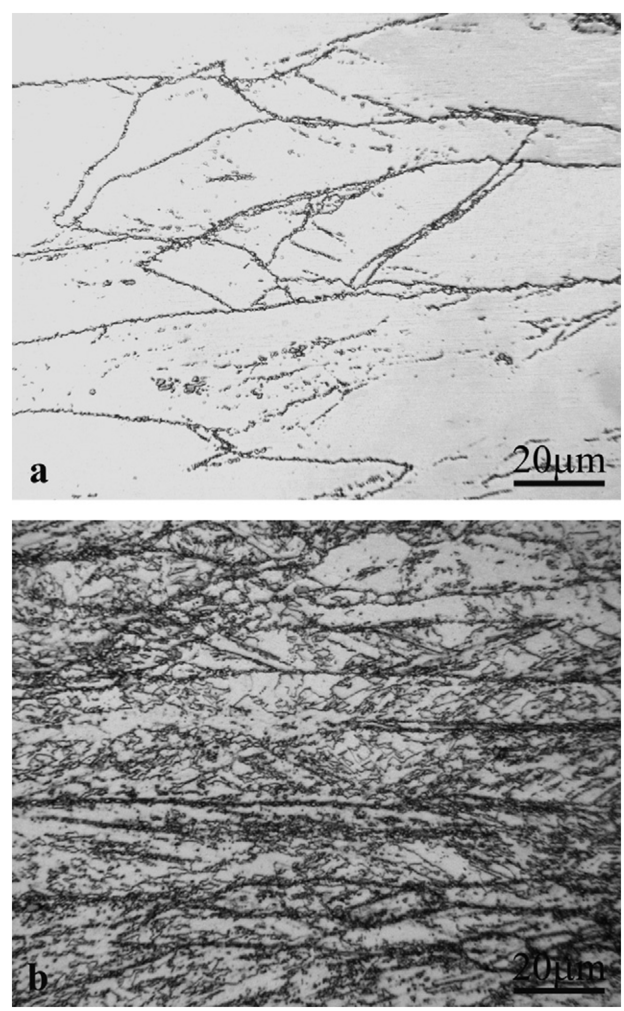

Fig. 2. Optical micrographs showing (a) pancake grains elongated in the rolling direction of the hot rolled steel and (b) substructures developed within the pancake grains after tensile deformation. Etchant: Kalling's reagent.