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High-strength steels hardened mainly by nanoscale NiAl precipitates

Z.B. Jiao,[a] J.H. Luan,[a] Z.W. Zhang,[b] M.K. Miller[c] and C.T. Liu[a,*]

[a]Center for Advanced Structural Materials, Department of Mechanical and Biomedical Engineering, College of Science and Engineering, City University of Hong Kong, Hong Kong, People's Republic of China

[b]College of Materials Science and Chemical Engineering, Harbin Engineering University, Harbin, Heilongjiang 150001, People's Republic of China

[c]Oak Ridge National Laboratory, Oak Ridge, TN 37831-6139, USA

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NiAl-strengthened high-strength steels usually have high Ni and Al contents in order to form hardening particles. Here, several new low-Ni steels are reported, which achieve a combination of relatively low cost, high strength and good ductility mainly through the precipitation of high number densities of nanoscale NiAl precipitates as characterized by atom probe tomography. The precipitation parameters are tuned by optimizing both alloy compositions and heat-treatment parameters. The strengthening effects of nanoscale NiAl and Mo/W-rich carbides are quantitatively analyzed and assessed.

Keywords: NiAl precipitate; Ferritic steel; Precipitation; Atom probe tomography; Mechanical property

High-strength steels have attracted significant interest in recent years due not only to their promising applications in automotive and aerospace industries but also to the serious emissions-related environmental problems facing mankind, such as global warming and smog [1–3]. Precipitation hardening is one of the most effective strengthening methods used in steels, and is achieved by producing a dispersion of particulates that serve as obstacles to dislocation movement [4]. The degree of strengthening obtained is highly dependent upon the metallic system involved, the volume fraction and size of the particles (or interparticle spacing), and the nature of the interaction of the particles with dislocations. Among various potential precipitates to be considered for precipitation hardening, NiAl particles constitute one of the most effective intermetallic strengthening phases [5–12]. The B2-ordered structure of the intermetallic compound NiAl is a derivative of the body-centered cubic (bcc) structure, and its lattice parameters are close to that of α-Fe, such that the NiAl phase satisfies the lattice coherent requirement in bcc ferritic alloys [13].

Two fundamentally different mechanisms may be used to form NiAl precipitates in ferritic steels. Firstly, NiAl precipitates can form homogeneously in the supersaturated ferrite matrix in steels [5–12]. In the Fe–Ni–Al system, there is a miscibility gap for disordered bcc-ferrite and B2-ordered NiAl, which makes NiAl precipitation possible [14]. The Ni contents of NiAl-precipitate-strengthened high-strength steels are generally larger than 7 wt.% [5–12]. Secondly, in Fe–Cu–Ni–Al-based steels, NiAl precipitates heterogeneously nucleate at the interface between the Cu particles and the ferrite matrix [15–20]. Ni and Al segregate to the Cu-particle–matrix interface, and their enrichment leads to the precipitation of NiAl-type intermetallic compounds surrounding the Cu particles, thereby forming a complex structure consisting of a Cu-rich core and a NiAl shell [15–20]. Interestingly, a high number density of nanoscale NiAl precipitates could be formed in low-Ni Cu-free steels (4–5 wt.% Ni) by optimizing both alloy compositions and heat-treatment parameters. Based on this finding, novel economical high-strength steels hardened by nanoscale NiAl precipitates have been developed. In this paper, relevant experimental results will be presented and the underlying mechanisms for nanoscale NiAl

* Corresponding author. Tel.: +852 3442 7213; fax: +852 3442 0172; e-mail: chainliu@cityu.edu.hk

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precipitation strengthening will also be quantitatively evaluated.

The chemical compositions of five steels with different Ni contents used in this study are listed in Table 1. For convenience, they are referred to as 0Ni, 1Ni, 2.5Ni, 4Ni and 5Ni steels. The five steels were melted and cast in a vacuum system back-filled with pure Ar cover gas in a laboratory-scale arc furnace, resulting in an ingot size of 50 mm × 15 mm × 3 mm. The as-cast ingots were cold rolled for multiple passes for a total reduction of ∼66%. The rolled plates were solutionized for 30 min at 900 °C for recrystallization, followed by water quenching to room temperature and then aging in the temperature range from 500 to 600 °C for various time periods up to 8 h.

Hardness measurements were conducted under a 200 g applied load and a dwell time of 15 s. The average hardnesses from six different measurements were reported. Sheet tensile samples with a cross-section of 3.2 mm × 1 mm and a gauge length of 12.5 mm were prepared by electrodischarge machining. Room-temperature tensile tests along the rolling direction of the samples were conducted on an MTS tensile testing machine at a strain rate of $10^{-3}\ s^{-1}$. Fracture surfaces were examined by scanning electron microscopy (SEM).

Thin TEM foils were prepared by a twin-jet electrochemical polisher at 35 V in a 5 vol.% $HClO_4$ methanol electrolyte at a low temperature. APT was performed with a CAMECA instruments local electrode atom probe (LEAP 4000X HR) in voltage-pulsed mode. A specimen temperature of 50 K, a pulse repetition rate of 200 kHz and a pulse fraction of 0.2 were used. Imago Visualization and Analysis Software version 3.6 were used for the three-dimensional reconstruction, composition analyses and the creation of isoconcentration surfaces. Nanoscale NiAl-precipitates were identified with the maximum separation method [21], with a maximum separation distance of 0.5 nm, a minimum of 20 Ni atoms in the precipitates and a grid resolution of 0.1 nm.

To determine the optimum aging condition for NiAl precipitation hardening, aging treatments at 500, 550, 575 and 600 °C for various periods of time were conducted. The hardness of the 5Ni steel as a function of aging time is shown in Figure 1a. At 500 °C, the hardness increases monotonically within the aging period of 8 h, indicating that the aging kinetics at this temperature is very slow. During aging at 550 °C, the hardness increases with annealing time and reaches a peak value of ∼510 HV at an aging time of 2 h, followed by a decrease due to an overaging effect. At an aging temperature of 575 °C, the steel shows a rapid rate of precipitation hardening and quickly reaches a peak hardness of ∼450 HV at an aging time of 0.5 h. At an aging temperature of 600 °C, no distinct hardening is observed and the hardness displays a slight decrease, implying that the Ni and Al concentrations are below the solubility limit of NiAl in ferrite at 600 °C. The above results indicate that the aging treatment at 550 °C provides the optimum condition for obtaining a substantial precipitation-hardening response within a reasonable period of time.

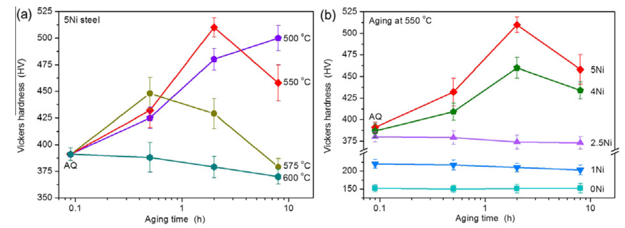

Fig. 1. (a) Hardness as a function of aging time for the 5Ni steel aged at 500–600 °C; and (b) hardness of the 0Ni, 1Ni, 2.5Ni, 4Ni and 5Ni steels after isothermal aging at 550 °C. Error bars represent the standard deviation of the six measurements for each data point.

The age-hardening response of the 0Ni, 1Ni, 2.5Ni, 4Ni and 5Ni steels after isothermal aging at 550 °C is presented in Figure 1b. The hardness of the 0Ni, 1Ni and 2.5Ni steels shows no appreciable change upon aging, suggesting no precipitation hardening with this aging condition in these steels. From a thermodynamic point of view, Ni has a considerable solubility in bcc Fe at 550 °C and a small amount of Ni addition would be dissolved in the matrix rather than form NiAl phases. In contrast, the hardness of the 4Ni steel increases rapidly with annealing time and reaches a peak value of ∼460 HV for an aging time of 2 h, but the increase in hardness is less pronounced compared with that of the 5Ni steel.

Room-temperature tensile tests were performed to further investigate the mechanical properties of the 4Ni and 5Ni steels. Tensile specimens of the 4Ni and 5Ni steels were solutionized at 900 °C for 30 min, water-quenched, and then aged at 550 °C for 2 h, corresponding to the peak-hardening condition for the two steels. The engineering stress–strain curves of the aged steels are shown in Figure 2. The two aged steels exhibit a high tensile strength of ∼1300–1500 MPa and a satisfactory elongation-to-failure of 10%, comparable to available high-Ni NiAl-strengthened steels, such as PH 13-8, Custom 475 and maraging steels [5–12]. In addition, these low-Ni steels show obvious large necking and reductions in area (∼47%), together with a microvoid coalescence fracture mode with fine dimples (Fig. 2, inset), indicating an excellent combination of relatively low cost, high strength and good ductility. To experimentally determine the hardening response from NiAl precipitates, the as-quenched specimens of the

Table 1. Alloy compositions (wt.%) of the steels studied (N < 0.005 wt.% for all the steels).

Alloy	Ni	Al	Mn	Mo	W	Nb	B	C
0Ni steel	0.05	0.97	1.47	1.55	1.63	0.06	0.013	0.047
1Ni steel	0.95	1.08	1.40	1.56	1.64	0.05	0.009	0.056
2.5Ni steel	2.40	1.08	1.56	1.60	1.56	0.06	0.014	0.048
4Ni steel	4.03	1.05	1.57	1.66	1.67	0.07	0.011	0.045
5Ni steel	4.97	1.09	1.52	1.61	1.65	0.06	0.012	0.055