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Correlation between disorder-order transformations in a Ni-based alloy and its mechanical properties

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ABSTRACT

It is demonstrated that the disorder-order transformations in a commercial Ni-Mo alloy with minor concentrations of Fe and Cr and the corresponding effect on mechanical strength are sensitive functions of the exact chemical composition. A slight change in composition within the specified limits of the alloy is found to change the nature of the ordered phases as well as the kinetics of the transformation and the mechanical strength. The results show that while the increase in tensile yield strength due to atomic order is accompanied by moderate decrease in tensile ductility, additional loss of ductility can occur at constant yield strength due to changes in morphology of the ordered microstructure during isothermal aging. It is also shown that the state of short-range order present in an otherwise disordered solid-solution acts as a pre-existing nucleus for the transformation, which accelerates the respective kinetics. However, elimination of the short-range order by cold work is found to decelerate the kinetics of the transformation. It is concluded that although the disorder-order transformations in the alloy investigated have detrimental effects on mechanical strength, some beneficial effects of technological importance can be realized.

1. Introduction

Addition of Mo to Ni is known to lower its stacking fault energy [1]. Therefore, during plastic deformation, dislocations tend to be confined to their original slip planes, which accelerates the strain hardening rate [2]. On the other hand, Mo is found to have relatively slow diffusivity in Ni due to its large atomic volume [1,3]. Also, Ni-Mo alloys with Mo content exceeding 15 wt% are distinguished by their outstanding resistance to reducing media such as hydrochloric acid [4]. Therefore, three generations of Ni-Mo alloys with commercial grades have thus far been developed for structural applications in the chemical process and petrochemical industries namely Hastelloy alloys B, B-2 and more recently B-3 with nominal compositions listed in Table 1 [4,5].

Binary Ni-Mo alloys with Mo contents such as those listed in Table 1 are well known to undergo long-range ordering transformations whereby the parent disordered face-centered cubic (fcc) structure is transformed into Ni_4Mo or $Ni_4Mo + Ni_3Mo$ when subjected to temperatures in the range of about 600–800 °C or during slow cooling from high temperatures [6]. Since such ordering transformations can result in severe embrittlement, extreme caution must be exercised during processing operations as well as during service [7–9]. However, it has been shown that under certain aging conditions, ordering in non-commercial Ni-Mo and Ni-Mo-Cr alloys can favor deformation by twinning, which maintains a relatively high ductility level [7,10–12].

In the case of commercial grade alloys such as those shown Table 1, the presence of minor elements particularly Fe and Cr can have important effects on the ordering behavior and corresponding properties [13]. Another important factor, which can further complicate the behavior of those alloys is cold work, which is encountered during thermo-mechanical processing of hardware items [14,15]. To elucidate the influence of exact chemical composition and cold work, the present study has been undertaken utilizing two heats of alloy B-2 with different compositions falling within the respective nominal composition illustrated in Table 1.

2. Experimental procedure

Table 2 illustrates the chemical compositions of the two heats of alloy B-2 included in the present investigation as determined by inductively coupled plasma-atomic emission spectroscopy except for the C concentration, which was measured by combustion calorimetry. Samples were in the form of 3 mm thick sheets and 25.4 mm thick plates. The sheet samples were used in tensile test experiments and microstructural characterization and the plates were used to determine the effect of cold work on the ordering behavior. Standard tensile test specimens with 50.8 mm gage length as well as 50.8 mm × 50.8 × 3 mm specimens for metallographic work were machined from the sheet samples. Prior to testing, the specimens were given the heat treatment recommended by the manufacturer (annealing at

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Table 1
Nominal compositions of commercial (Ni-Mo)-based alloys (wt%).

Alloy	Ni	Mo	Fe	Cr	Co	Mn	Si	P	S	C
B	Bal.	26–30	5*	1*	2.5*	1*	1*	0.04*	0.03*	0.05*
B-2	Bal.	26–30	2*	1*	1*	1*	0.1*	0.04*	0.03*	0.02*
B-3	Bal.	27–32	1–3	1–3	1*	1*	0.1*	0.03*	0.01*	0.01*

Table 2
Chemical compositions of the heats investigated (wt%).

Element	Heat 1	Heat 2
Ni	71.39 ± 1.4	69.11 ± 1.3
Mo	26.84 ± 0.5	28.79 ± 0.6
Fe	0.84 ± 0.02	1.10 ± 0.02
Cr	0.53 ± 0.01	0.62 ± 0.01
Co	0.16 ± 0.003	0.10 ± 0.002
Mn	0.19 ± 0.004	0.22 ± 0.005
Si	0.02 ± 0.0005	0.03 ± 0.0005
P	0.01 ± 0.0002	0.01 ± 0.0002
S	≤ 0.01	≤ 0.01
C	≤ 0.01	≤ 0.01

1065 °C for 15 min followed by water quenching) [16], except for some metallographic specimens, which were furnace- cooled to compare the resulting microstructures. All water-quenched sheet specimens were aged for up to 1000 h at 600, 700 and 800 °C. The respective tensile strength was determined as function of aging time (1/4, 1/2. 1, 4, 8, 24, 100 and 1000 h) at each temperature. Annealing of the plate sample was carried out at 1065 °C for 30 min followed by water quenching, 50% cold reduction and then aging for up to 1000 h at 800 °C. The corresponding effect on the mechanical strength was evaluated from Vickers microhardness as functions of aging time.

Optical microscopy, scanning electron microscopy (SEM), x-ray diffraction, transmission electron microscopy (TEM) combined with energy dispersive x-ray spectroscopy and Auger electron spectroscopy were used to correlate the observed mechanical strength with microstructures. Specimens for optical microscopy used to reveal the gross grain structure were polished and etched in a solution of 80% hydrochloric acid by volume and 20% by volume of 15 mol chromic acid. X-ray diffractometry experiments for phase analysis were conducted on polished specimens using Cu-K_α radiation. Thin foils transparent to electrons for TEM experiments were thinned by first grinding specimens down to about 0.5 mm thickness and then electro-polishing in a solution of 30% nitric acid by volume in methanol. All experiments were carried out using a microscope operating at 200 keV. An Auger microprobe equipped with in-situ fracture device was employed to generate depth profiles of Mo as a function of distance from grain boundaries in selected ordered specimens using a sputtering rate of 1 nm/min. Henceforth, all crystallographic notations of electron diffraction patterns are given in terms of the face-centered cubic (fcc) structure.

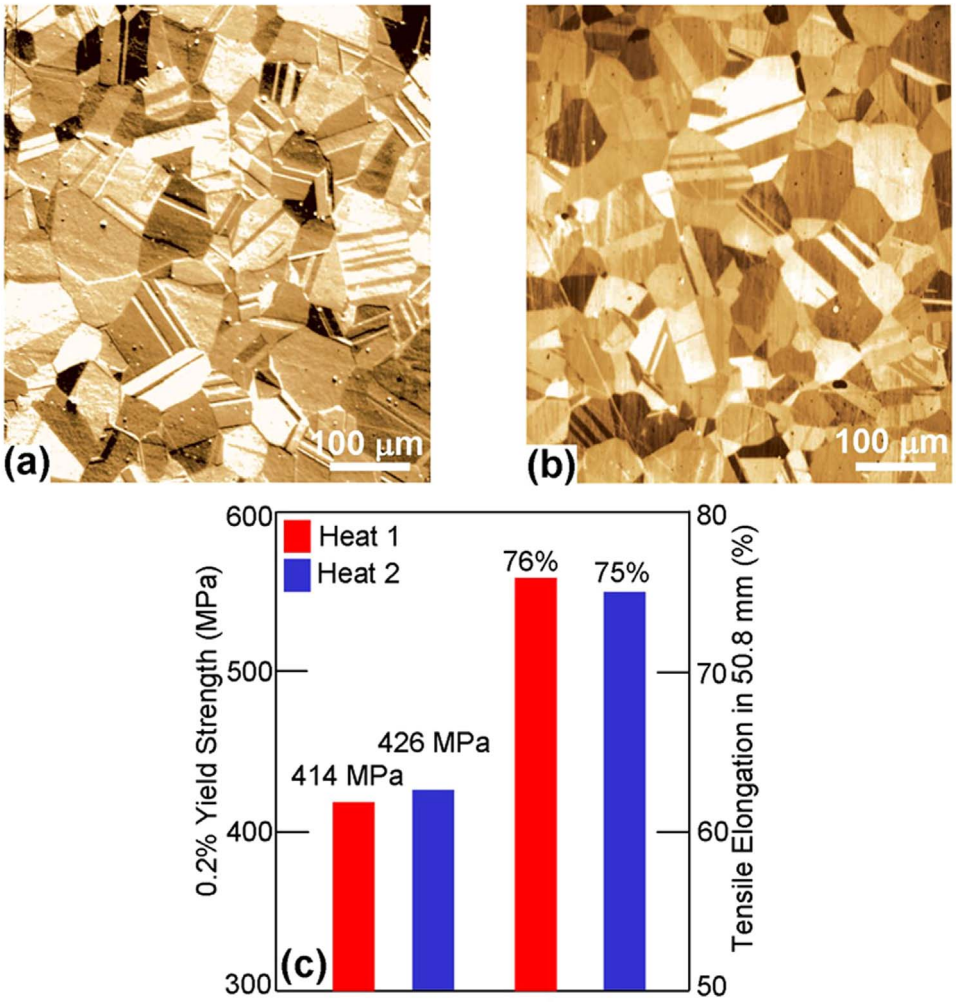

Fig. 1. Optical microstructures and tensile properties of as quenched heats. (a) Grain structure of heat 1. (b) Grain structure of heat 2. (c) Comparative room-temperature tensile properties.