Materials Science & Engineering A 738 (2018) 38–43

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

Short communication

Generation of high-performance Ni-Cr-Mo-based superalloys via γ to DO_{22} superlattice ordered phase transformation upon addition of trace alloying elements

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ARTICLE INFO

Keywords:
Ni-Cr-Mo-based alloys
Niobium
DO_{22} superlattice
Creep strain
Thermal stability

ABSTRACT

The mechanical properties of Ni-Cr-Mo-based alloys with tailored ordered phases were investigated. Introduction of niobium induced the formation of a DO_{22} superlattice and stabilized this structure by avoiding its precipitation in ternary Ni-Cr-Mo. The tetragonal structure and high thermal stability of DO_{22} resulted in alloys with higher hardness (13 GPa) and the Young's modulus (225 GPa). Moreover, the sample containing the DO_{22} phase showed low creep strains and creep strain rates at holding time.

1. Introduction

Ni-Cr-Mo-based superalloys have been widely used in the industry because of their superior corrosion, oxidation and creep resistances [1–3]. High-performance Ni-Cr/Mo-Mo/Cr alloys can be prepared by precipitation of tailored nanoscale ordered phases, such as $C11_b$ (Pt_2Mo-type), DO_{22}, and D1a superlattices [4–8]. While the Pt_2Mo-type and DO_{22} phases provide Ni-Mo-based alloys with relatively high ductility, the poor thermal stability of D1a causes a nearly complete loss of ductility [9,10]. High strength and good ductility are typically associated with high anti-phase boundary (APB) energies and changes in the deformation mode (i.e., from dislocation slip to $\{111\} < 112 >_{fcc}$ twinning,), respectively [11]. An ultrastrong steel strengthened with an ordered Ni(Al, Fe) phase with B2 structure has been recently prepared [12]. This material showed very high age-hardening responses and superior (by 1.1 GPa) yield strengths while maintaining the ductility.

Despite these efforts, the stability of the DO_{22} superlattice in these alloy systems remains unsolved, and only the Pt_2Mo-type phase can stabilized in the equilibrium in Ni-Cr-Mo alloy systems [13,14]. This hinders the utilization of the DO_{22} phase for manufacturing high-performance alloys. A stable DO_{22} phase has been shown to precipitate in Ni-Mo and Ni-Cr-W alloy systems upon alloying with Nb, Ti, and Ta [15–18], however, the mechanism behind the formation of this phase upon addition of trace alloying elements in Ni-Cr-Mo alloy systems is not fully understood, although a different evolution behavior of ordered phases in the Ni-Cr-Mo/W and Ni-Mo alloy systems has been proposed. Apart from strengthening phases, other characteristics of the alloys must be considered. Thus, the applications of Ni-Cr-Mo alloys require these materials to be subjected to significant cyclic stress, and the creep behavior of the alloy must be established under service conditions. It was demonstrated [19,20] that trace alloying is an efficient way to improving the mechanical properties of alloys. In this work, ordered phases tailored by trace alloying were prepared and their effect on the mechanical properties of Ni-Cr-Mo-based alloys were investigated by nanoindentation methods with two primary objectives: (i) confirm the precipitation of a stable DO_{22} ordered phase in the Ni-Cr-Mo alloy and (ii) confirm the formation of a high-performance Ni-Cr-Mo alloy upon precipitation of the DO_{22} phase.

2. Materials and experimental procedures

Ni-28Cr-5Mo-xNb alloys (x = 0 and 2 at%, NiCrMo and NiCrMo-Nb, respectively) were prepared by repeatedly (five times) melting a mixture of high purity metals (99.99%) in a vacuum electro-arc furnace to obtain a homogeneous composition. The ingot was subsequently homogenized at 1200 °C for 24 h in a vacuum environment followed by furnace cool. Subsequently, the specimens were aged at 600 °C for 240 h, and subsequently water quenched to precipitate several stable ordered phases such as $C11_b$ (Pt_2Mo-type), DO_{22} and D1a based on the research results reported in the literature [5,9,11]. Moreover, the same specimens were also aged at elevated temperature of 700 °C for 240 h to identify the thermal stability of different ordered phases.

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https://doi.org/10.1016/j.msea.2018.09.093
Received 15 June 2018; Received in revised form 21 September 2018; Accepted 24 September 2018
Available online 25 September 2018

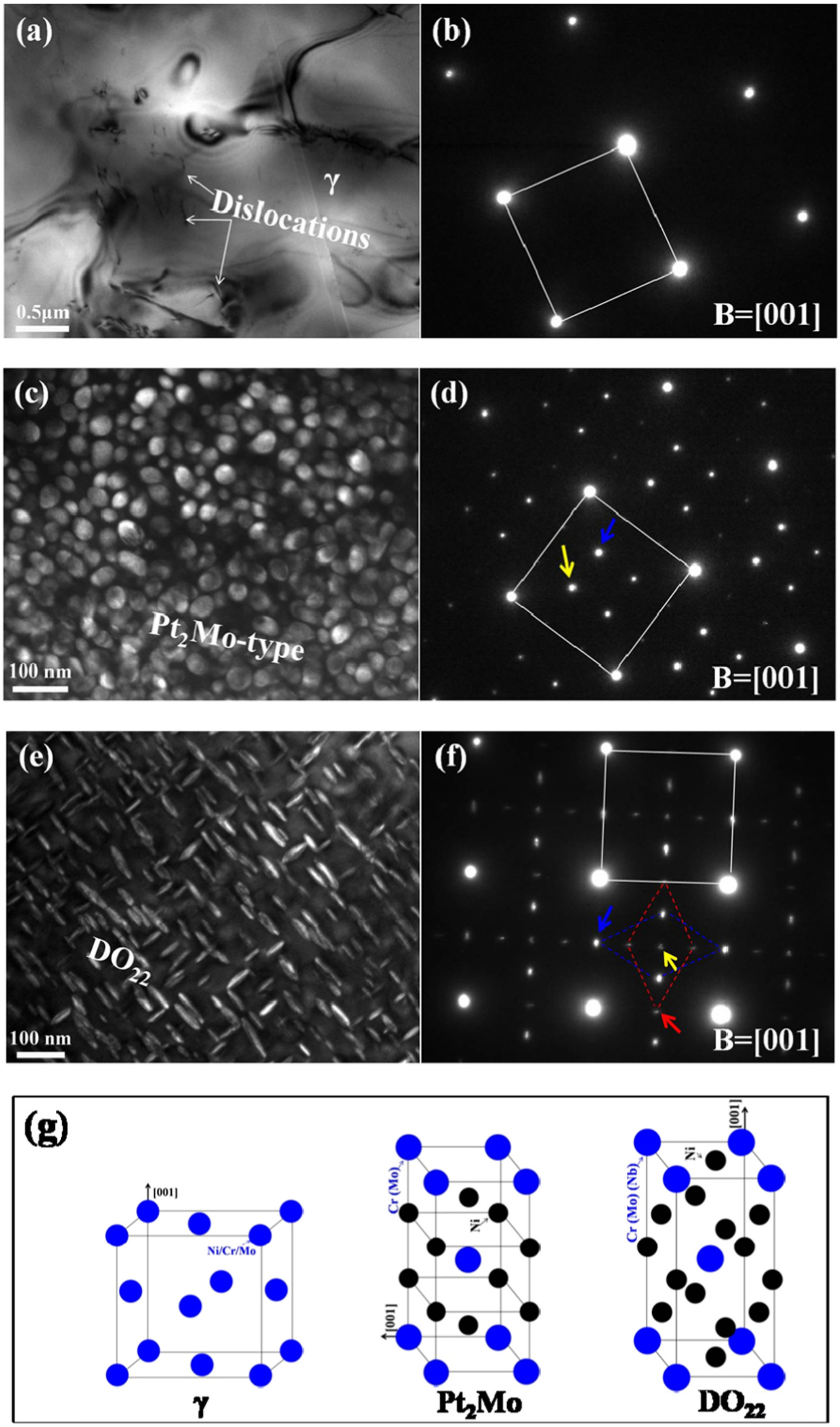

Fig. 1. TEM images and the corresponding SAED patterns of the samples. (a, b) as-quenched NiCrMo alloy, (c, d) aged NiCrMo alloy at 600 °C for 240 h, (e, f) aged NiCrMo-Nb alloy at 600 °C for 240 h, and (g) crystal structure of the γ, Pt_2Mo-type, and DO_{22} phases.