Intermetallics 19 (2011) 206–211

Contents lists available at ScienceDirect

Intermetallics

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

Effect of withdrawal rate on microstructure and mechanical properties of a directionally solidified NiAl-based hypoeutectic alloy doped with trace Hf and Ho

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A R T I C L E   I N F O

Article history:
Received 12 June 2008
Accepted 31 July 2008

Keywords:
A. Nickel aluminides, based on NiAl
B. Mechanical properties at ambient temperature
B. Mechanical properties at high temperatures
C. Crystal growth
D. Microstructure

A B S T R A C T

The hypoeutectic alloy, with nominal composition NiAl–31Cr–2.9Mo–0.1Hf–0.05Ho (at.%), was directionally solidified at three different withdrawal rates by liquid metal (Sn) cooling technique. Microstructural examination reveals that directional solidification gave rise to a shift in the coupled zone for the eutectic growth towards the Cr(Mo) phase. With the withdrawal rates increasing from 3 mm/min to 15 mm/min, the volume fraction of primary dendritic NiAl increases from 21.1% to 25.9%, while the size and the arm spacing of NiAl primary dendrite reduces simultaneously. The room temperature (RT) fracture toughness and the tensile strength at RT and elevated temperature (1373 K) present the valley value at intermediate rate (8 mm/min) among the withdrawal rate range which could be attributed to the decrease in volume fraction of eutectic NiAl/Cr(Mo) microstructure and the refinement of microstructure resulted from the increase of withdrawal rates. In terms of RT tensile elongation, the DS alloy grown at different withdrawal rates all break with no plastic flow.

1. Introduction

In spite of a series of attractive properties, such as density, oxidation, melting point and corrosion, the development of NiAl alloy as replacements for superalloys in high-temperature structural materials application has been limited by the difficulty in designing alloys with optimum combination of elevated-temperature creep strength and room temperature (RT) fracture toughness [1,2]. In an attempt to make NiAl a viable structural material, researchers make use of directional solidification technique to develop NiAl in situ composites [3]. In particular, the NiAl–Cr(Mo) eutectic system has been extensively studied [4–8].

Directionally solidified (DS) NiAl–Cr(Mo) eutectic system shows that both RT fracture toughness and elevated temperature strength are better than single-phase NiAl. For instance, the fracture toughness of DS NiAl–28Cr–6Mo at room temperature is up to about 24.1 $MPam^{1/2}$. However, all this improved properties require a perfectly aligned DS microstructure. According to the constitutional supercooling theory, solidification parameter G/R value (G means thermal gradient; R means withdrawal rate) influences the Solid/Liquid (S/L) interface morphology evolution. With constant thermal gradient, $G = 80–100$ K/cm, at the S/L interface, perfectly aligned eutectic microstructures develop in the NiAl/Cr(Mo) system only when the withdrawal rate, R, is typically less than 25 mm/h [9,10]. This rate is generally too slow for economic commercial production of any alloy even if it is demonstrated to possess all the benefits for high-temperature structural materials. Previous works have shown that faster withdrawal rate resulted in imperfect DS microstructure [11], however, the faster rate also led to a decreased interlamellar spacing, in accordance with the Jackson–Hunt relationship [12]: $\lambda^2 R$ = constant. The decrease in room temperature fracture toughness caused by imperfect DS microstructure may be compensated by smaller interlamellar spacing at faster withdrawal rate. Therefore, directional solidification at faster withdrawal rate possesses more application value.

In addition, Hf is an effective strengthening element for NiAl alloy at elevated temperature [13,14]. DS NiAl–Cr(Mo)–0.1Hf shows higher stress rupture strength than that of superalloy Rene 80 at elevated temperature [15]. Once the addition of Hf element is up to 0.4%, this alloy contains block Heusler phases (Ni_2AlHf) existing on the eutectic cell-boundary and shows low fracture toughness [16]. In order to enhance the bonding of the eutectic cell-boundary, rare earth element such as Y, La, Ce, Nd and Dy are added

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0966-9795/$ – see front matter
doi:10.1016/j.intermet.2010.08.013

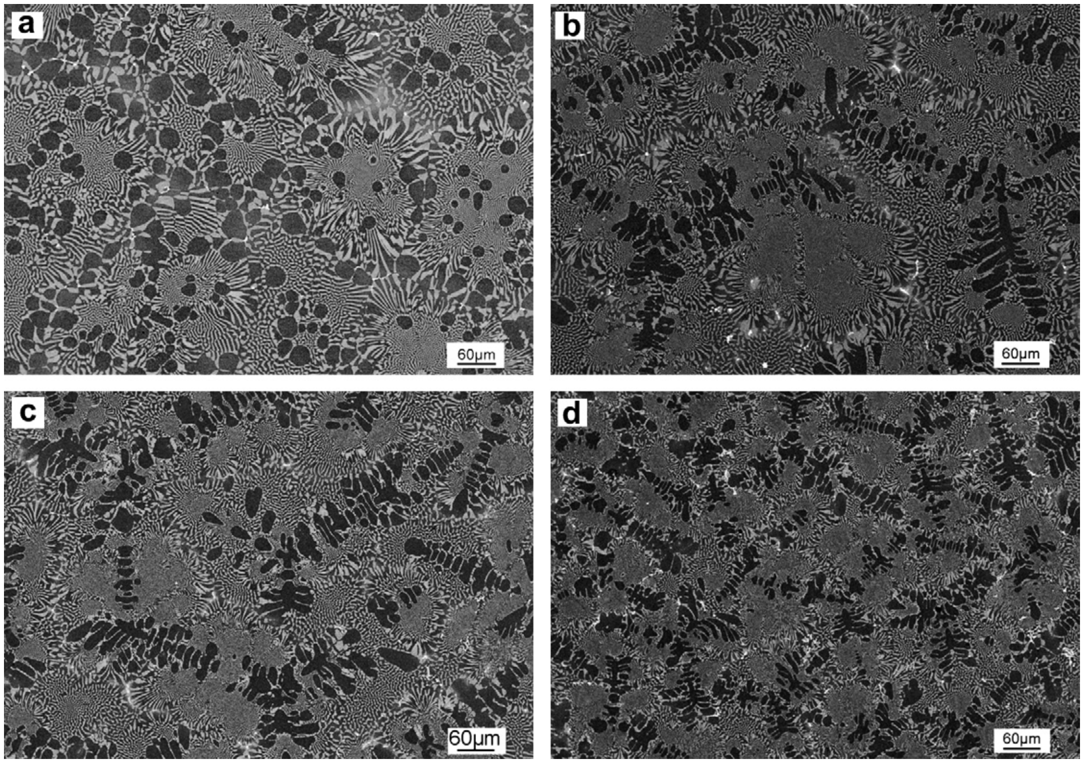

Fig. 1. SEM BSE (back-scattered electron) images of (a) as-cast alloy, and DS alloy along transverse sections with various withdrawal rates: (b) 3 mm/min, (c) 8 mm/min, (d) 15 mm/min.

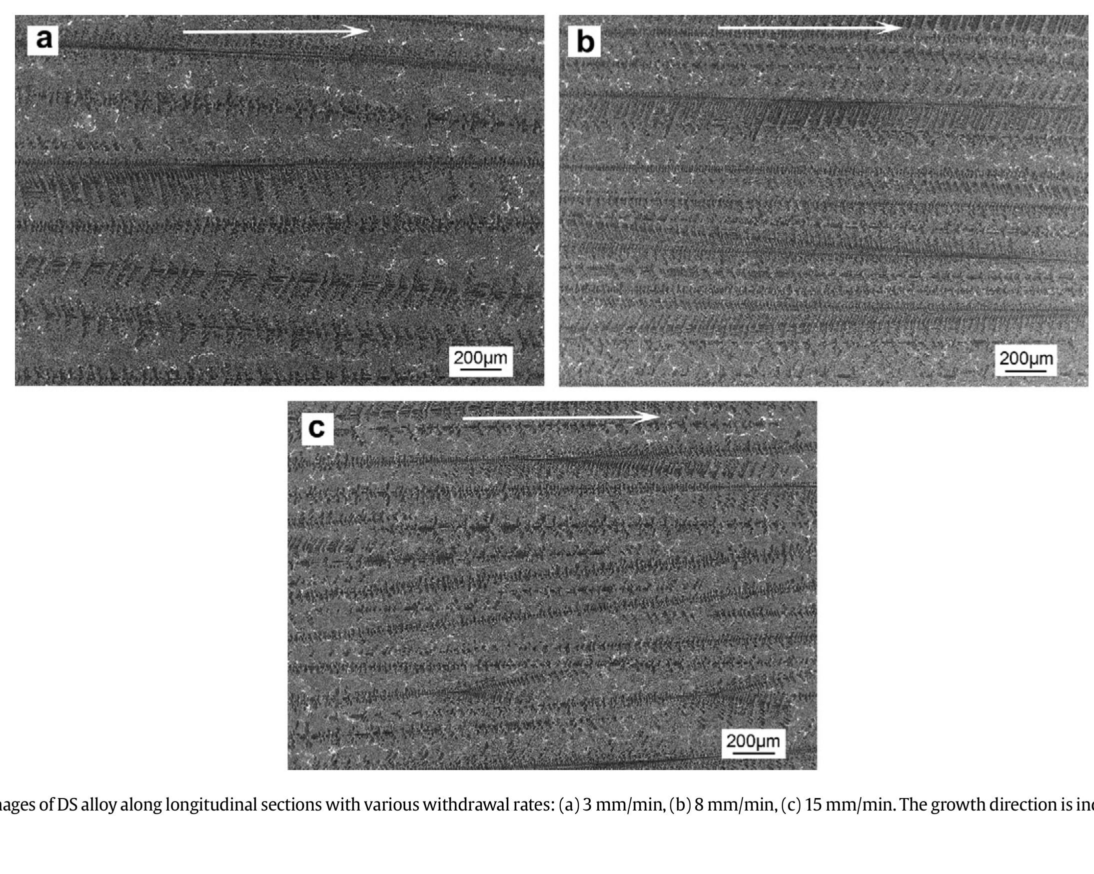

Fig. 2. SEM BSE images of DS alloy along longitudinal sections with various withdrawal rates: (a) 3 mm/min, (b) 8 mm/min, (c) 15 mm/min. The growth direction is indicated with arrows.