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Ductility improvement of intermetallic compound NiAl by unidirectional pores

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ABSTRACT

Compression tests were carried out for lotus-type porous NiAl at room temperature to verify its compressive properties when the structure of the material was controlled to ensure the existence of pores. The lotus-type porous NiAl was fabricated by unidirectional solidification in a pressurized hydrogen atmosphere. The results of the compression tests showed that the toughness of the porous NiAl was increased relative to that of the nonporous specimens. The cylindrical pores contributed to the toughening of the porous specimens by blunting crack tip and multi-cracking at pores. The difference between the aligned directions of the cylindrical pores caused the mechanical anisotropy of the specimens between different solidification directions to the compressive directions.

1. Introduction

The intermetallic compound, NiAl, with an ordered bcc structure(B2) possesses many attractive properties for use in a wide range of engineering applications, — such as a high melting temperature, low density, high stiffness and good oxidation resistance [1,2]. However, its low ductility and toughness at room temperature, as well as its poor creep resistance and strength at elevated temperature, are major obstacles to its practical use. In recent years, there have been many attempts to improve the low-temperature ductility and toughness of NiAl by controlling the structure of the matrix through the addition of alloying elements [3,4] and specific processes, especially by directional solidification [5,6].

Lotus-type porous metals which have cylindrical pores in the matrix exhibit superior mechanical properties to those of porous materials with spherical pores. In addition, they have anisotropic mechanical and physical properties that are derived from their pore morphology. Although the mechanical properties of lotus-type porous metals with a ductile matrix have been extensively investigated, with the exception of TiAl, there have been far fewer studies on brittle materials [7,8]. In the study on the mechanical properties of lotus-type porous TiAl, its deformation strain was found to be higher than that of nonporous solids under compressive loads [8]. Recently, the intermetallic compounds, NiAl and Ni_3Al [9], were fabricated, but their mechanical properties were not reported. The present study aims to verify the compressive properties of lotus-type porous NiAl when the structure of the material is controlled to ensure the existence of pores.

2. Experimental

Stoichiometric NiAl raw ingots were prepared by arc melting in a vacuum with pure nickel (99.9%) and aluminum (99.99%) (Sumitomo Metal Technology, Inc., Japan). Rods of 10 mm in diameter and 170 mm in length were cut from the raw ingots by wire electro-discharge machining (AQ325L, Sodick Corp.). The continuous zone melting technique was carried out to produce lotus-type porous rods in a hydrogen atmosphere at a pressure of 2.5 MPa. This technique is a method of a directional solidification. The specific process of this technique was described in elsewhere [7,10]. Nonporous rods were produced by the same technique in an argon atmosphere at a pressure of 2.5 MPa to compare their compressive behavior with those of the porous specimens. The transference velocity was 330 μm/s for both types of rods. The porosity, p, of the lotus-type porous NiAl was calculated using the following equation:

$$p = \left(1 - \frac{\rho}{\rho_0} \times 100(\%)\right), \quad (1)$$

where ρ and ρ_0 are the densities of the lotus-type porous and nonporous specimens, respectively. The pore diameter was determined by image analysis software (Image-pro plus, Media Cybernetics Inc.).

Compressive specimens ($5 \times 5 \times 7.5\ mm^3$) were cut by wire EDM from the porous and nonporous rods with different solidification directions. The solidification direction, which indicates the pore axis of the lotus-type porous rods, was parallel and perpendicular to the compressive direction. Each specimen was homogenized for 24 h at

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1474 K in a vacuum of less than 6.6×10^{-6} Torr to achieve a uniform dispersion of the β-NiAl phase. X-ray diffraction was used to analyze the phases of the Ni-Al binary system before and after the homogenization heat treatment. Compression tests were carried out using a universal testing machine (Model 5569, Instron Corp.) at room temperature (RT) with a strain rate of 1.1×10^{-3} /s. The cross-sections of the lotus-type porous rods were polished and then chemically etched with a solution made up of 90 mL of H_2O, 10 mL of H_2O_2 and 10 mL of HCl. Subsequently, their surface structure was examined by optical microscope (VHX200, Keyence Corp.), and scanning electron microscope (Jeol 5500, Jeol Ltd.) was used to observe the behavior of the cracks on the specimens after the compression tests. The surface of the compressive specimens was ground by SiC abrasive papers up to 2000 grit, and polished with 1 μm diamond paste.

3. Results and discussion

Cylindrical pores elongated along the solidification direction were present in the rods, as shown in Fig. 1. Furthermore, columnar grains were observed which were aligned with solidification direction, which is an inherent feature of directional solidification. The average pore diameter of the lotus-type porous NiAl was measured to be 388 ± 109 μm and the average porosity was 37.0 ± 3.9%.

Fig. 2 shows the results of the compression tests for the porous and nonporous NiAl specimens. The peak point was taken as both the compressive strength and fracture strength, as stated in [11]. Before the compression tests, each specimen was fully homogenized, and the presence of only β phase was confirmed by XRD. The compressive strength of the nonporous NiAl was higher than that of the porous NiAl. The yield strength and compressive strength decreased with increasing porosity. The most obvious feature of the compressive stress–strain curve was that plastic behavior appeared after yielding in the porous specimens at stresses up to their peak stress. However, the nonporous specimens were fractured after yielding and plastic behavior was not observed in the stress–strain curve, which is an inherent feature in brittle solids. Therefore, the deformation strain of the porous specimens increased by five to six times compared to that of nonporous specimens.

The anisotropic mechanical properties of the specimens with different solidification directions in relation to the compressive direction are given in Table 1. Both the yield strength and fracture strength of the porous and nonporous NiAl with the pore axis parallel to the compressive direction were higher than those with the pore

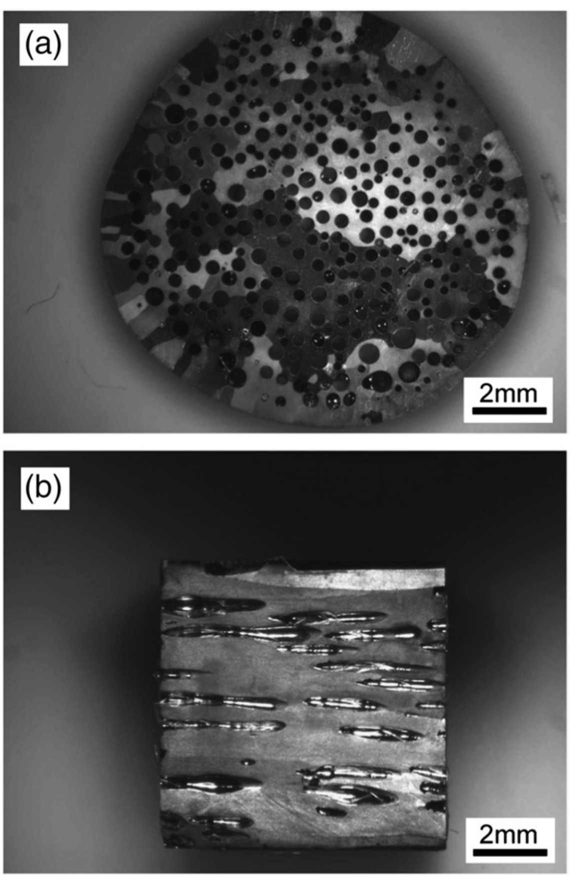

Fig. 1. Optical micrographs of (a) transverse and (b) longitudinal cross sections for the lotus-type porous NiAl rods fabricated by the continuous zone melting technique with a mean pore diameter of 388 ± 109 μm and a mean porosity of 37.0 ± 3.91%. Cylindrical pores were present inside the lotus-type porous NiAl rod and were oriented parallel to the solidification direction.

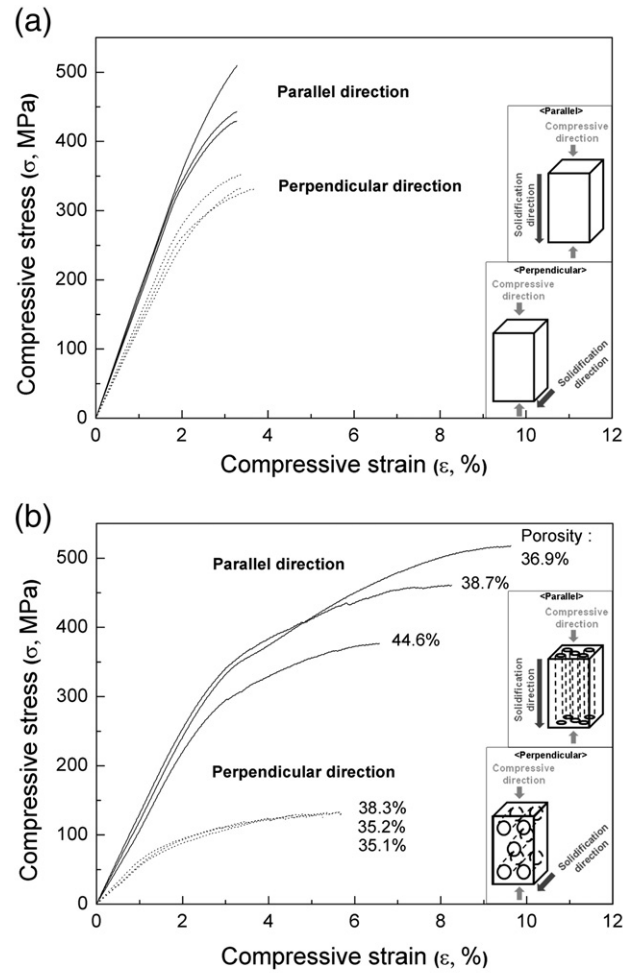

Fig. 2. Compressive stress–strain curves of (a) nonporous and (b) lotus-type porous NiAl. The specimens with the pore axis parallel to the compressive direction are illustrated by normal lines and those with the pore axis perpendicular to the compressive direction are illustrated by dashed lines. The compression tests were carried out with a strain rate of 1.1×10^{-3} /s.

Table 1
Mechanical properties of lotus-type porous and nonporous NiAl with solidification direction parallel and perpendicular to the compressive direction.

Specimen	Relation of pore axis to compression direction	Yield stress (MPa)	Fracture strength (MPa)	Absorbed energy/ volume(MJm^{-3})
Lotus	Parallel	312	452	19.0
	Perpendicular	85	128	5.2
Nonporous	Parallel	417	467	9.8
	Perpendicular	298	339	7.3