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Microstructure, properties and application of YAl_2 intermetallic compound as particle reinforcements

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ABSTRACT

An yttrium aluminum (YAl_2) intermetallic compound ingot was prepared in an induction furnace under vacuum. The microstructure of YAl_2 ingot was characterized by optical microscopy, scanning electron microscopy, and X-ray diffraction. The load bearing response of YAl_2 intermetallic was investigated and compared with SiC ceramic by indentation combined with optical microscopy and scanning electron microscopy. Additionally, the tensile properties of the Mg–Li matrix composites reinforced with ultrafine YAl_2 particles fabricated by planet ball milling were tested. The results show that the intermetallic compound ingot in this experiment is composed of a main face-centered-cubic structure YAl_2 phase, a small amount of YAl phase, and minor Y and Al-rich phases. YAl_2 intermetallic compound has excellent stability and shows better capability in crack resistance than SiC ceramic. The YAl_2 intermetallic compound has better deformation compatibility with the Mg–14Li–3Al matrix than SiC reinforcement with the matrix, which leads to the superior resistance to crack for YAl_{2p}/Mg–14Li–3Al composite compared to SiC_p/Mg–14Li–3Al composite.

1. Introduction

The rare-earth intermetallic compound YAl_2 has attracted considerable attention because of its interesting, anomalous physical properties. In the work of Hasegawa and Yanase [1], the Fermi surface and energy band structure of YAl_2 was investigated by calculation. The cross sectional area of the tenth-band Fermi surface agrees well with an experimental result of the de Hass-van Alphen effect measurement [2]. Bauer et al. [3] studied the thermal conductivity of YAl_2 compound from 4.2 K to room temperature and found that the lattice thermal conductivity of YAl_2 is negligible for temperatures lower than 20 K as well as for temperatures above about 200 K. The standard molar enthalpy of formation of YAl_2 calculated by first principles, based on high temperature calorimeter data, is $-152\ \mathrm{kJ\ mol^{-1}}$ at 1473 K, in the work of Jung et al. [4]. Krčmar and Fu [5] found that the point defect structure of YAl_2 is dominated by the anti-site defects on the larger atom-rich side of the stoichiometry. Duman and Tutuncu [6] investigated the structural, elastic, and electronic properties of YAl_2 by ab initio calculation. The results suggest that YAl_2 is not likely to be a superconductor. Huang et al. [7] analyzed the structural stability, thermodynamic stability, elastic properties and electronic structure of YAl_2 phase by first principles calculations. The calculated results indicate that YAl_2 phase has a strong alloying ability and a strong structural stability. Although the physical properties of YAl_2 intermetallic compound have been investigated experimentally and theoretically extensively, there are few reports about the microstructure and mechanical properties of YAl_2 intermetallic compound and for the application of YAl_2 intermetallic compound as reinforcements.

Recently, some intermetallic compounds such as TiAl, Ti_3Al, and Ni_3Al were used to reinforce metal matrix composites [8–10]. Unlike ceramic particles, intermetallic compound consists of two types of atomic bonds, i.e. metal and covalent bonds. Therefore, the bonding between these reinforcing intermetallic particles and the matrix is greatly improved [11]. By adding the intermetallic particles, the tensile strength and yield strength of composites reinforced may be enhanced, meanwhile maintaining good ductility. As other intermetallic compounds, YAl_2 has high melting temperature (1748 K), high Young's modulus (158 GPa), high hardness (HV 645), and relatively low coefficient of thermal expansion ($10^{-5}\ \mathrm{K^{-1}}$). Therefore, YAl_2 intermetallic compound particles are considered to have the potential of application as reinforcement in composites. Additionally, the mechanical properties of metal matrix composites are improved with decreasing particle size, especially when the particle size is in the submicron and nanometer range [12,13].

In this paper, the microstructure of YAl_2 ingot was characterized to evaluate YAl_2 for particle reinforcement in composites.

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The bearing response and crack resistance of YAl_2 intermetallic were investigated comparing with SiC ceramic. Then, the YAl_2 particles were fabricated by planet milling and added into the Mg–Li matrix alloys, forming YAl_{2p}/Mg–14Li–3Al and YAl_{2p}/Mg–14Li–1Zn composites. The tensile properties of the composites were tested.

2. Experimental

2.1. Materials

YAl_2 ingots (62 wt% Y and 38 wt% Al) were prepared by melting a mixture of pure yttrium (99.9 mass%) and aluminum (99.9 mass %) metals in a purified argon atmosphere. The YAl_2 compound is selected according to the binary Al–Y phase diagram shown in Fig. 1 [14]. The ingot is expected to provide single YAl_2 phase.

The YAl_2 ingot was mechanically crushed and sieved under 3 μm after planetary ball milling (QM-1SP). The ball to powder weight ratio was 4:1. The milling times were 2, 10, 20, and 30 h. The rotation speed (cup speed) was 400 rpm.

Mg–14Li–3Al and Mg–14Li–1Zn were used as matrix alloys. Their composites with YAl_2 particle (size smaller than 3 μm) reinforcements were prepared by stir-casting in a resistance furnace under protective argon atmosphere. The structure of the Mg–14Li–3Al matrix is body centered cubic and the optical micrograph of the Mg–14Li–3Al alloy is shown in a previous paper [15]. There is a single phase in the Mg–14Li–3Al matrix alloy with an average grain size of 0.55 mm.

Commercial SiC compound was used and SiC_p/Mg–14Li–3Al composite was prepared by stir-casting in a resistance furnace under a protective argon atmosphere.

2.2. Characterization

The microstructure and composition of YAl_2 ingot were characterized using optical microscope (OM; XJP3C), scanning electron microscope (SEM; Quanta 2000), and X-ray diffractometer with Cu Kα radiation (XRD; D/MAX-2000). Samples for OM and SEM were prepared by mechanical grinding and polishing, and finishing with an etching solution of 11 ml nitric acid, 4 ml hydrochloric acid and 35 ml water.

The morphology and structure of YAl_2 particles were examined by SEM (S4800) and XRD with Cu Kα radiation (D/MAX-2000). YAl_2 particle size distribution was analyzed with an image-analysis software (Image-pro-plus) based on six SEM images.

2.3. Load bearing response tests using micro and nano-indentation

The microindentation morphology on YAl_2 and SiC compounds was presented by OM after the Vickers microhardness testing (HXZ-1000) with a 0.5 kgf load and a dwell time of 15 s.

The characteristics of YAl_{2p}/Mg–14Li–3Al and SiC_p/Mg–14Li–3Al interfaces were investigated using single nanoindentation marks which were made on particle/matrix interface to generate some cracks. Details of the nanoindentation tests were given in a previous paper [16]. The microstructure after nanoindentation in interface was observed by SEM (S4800).

2.4. Mechanical properties

The fracture toughness of YAl_2 intermetallic was determined from the following equation [17] and the result was average of 16 microindentations:

$$K = 0.016[E/H]^{1/2} P/(L)^{3/2}$$

where P is the load (kgf), H is the hardness value, L is the average crack length, and E is the Young's modulus (158 GPa).

Crack resistance of reinforcement in YAl_{2p}/Mg–14Li–3Al and SiC_p/Mg–14Li–3Al composites was tested on a universal testing machine (Instron 5569) using single edge notched beam (SENB) method. The test machine was operated in displacement control mode at a cross-head speed of 0.5 mm/min. The beams were machined with a span length of 16 mm, and a 2 mm length notch was made by electric discharge machining.

Tensile properties of the Mg–Li alloys reinforced by YAl_2 were evaluated at room temperature at a strain rate of 0.5 mm/min.

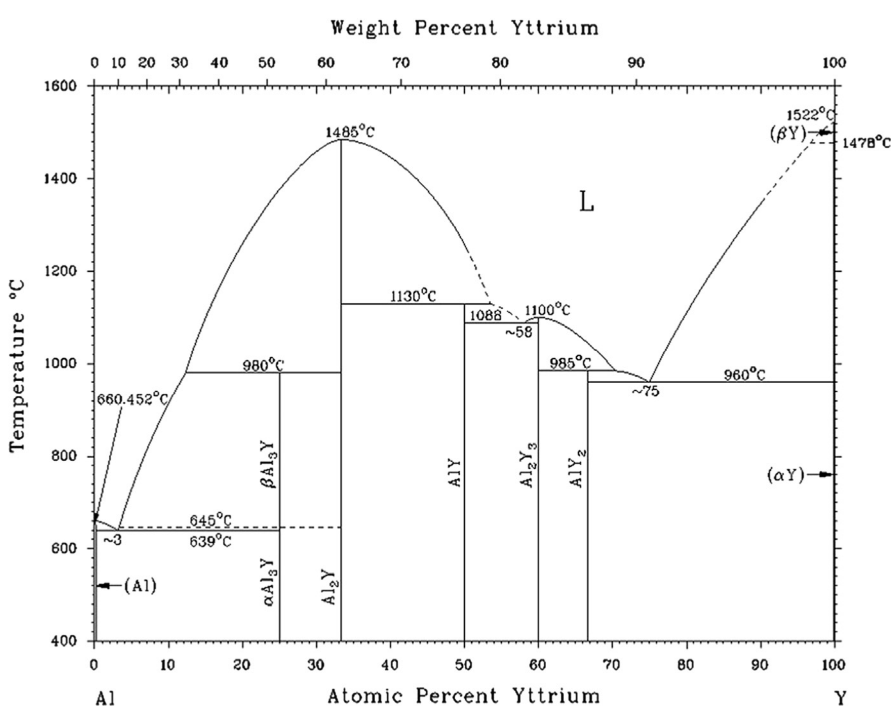

Fig. 1. Al–Y binary phase diagram [14].