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Original Research Paper

Spark plasma sintering of gas atomized AlNiYLaCo amorphous powders

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ABSTRACT

Highly dense bulk samples were fabricated by spark plasma sintering (SPS) through a combined devitrification and consolidation process of partially amorphous AlNiYLaCo gas-atomized powders. The microstructure and mechanical properties were investigated in detail. The microstructure of the consolidated samples is mainly nanocrystalline. Moreover, the sintered sample exhibits a compressive fracture strength of approximately 1058.6 MPa and a 4.8% compressive plastic strain prior to fracture. Our results indicate that bulk nanocrystalline alloy samples can be fabricated via devitrification for amorphous precursors and powder metallurgy.

1. Introduction

Bulk metallic glasses (BMGs) with long-range disordered atomic structures give rise to unique mechanical and physical properties, such as high strength and elasticity, and are being considered for a wide range of applications. Many glass-forming alloy systems have been explored, such as Zr-, Cu-, and Pd-based systems [1–4]. Al-based amorphous alloys with high specific strength have been researched and developed in recent years. However, a maximum size of 1 mm for Al-based amorphous alloys in bulk form was obtained using the conventional casting method in 2009 due to their limited glass-forming ability (GFA), which severely restricts actual applications of this type of material [5]. In contrast, amorphous, partially amorphous, and nanocrystalline Al-based alloys have attracted widespread attention as potential candidates for structural and/or functional applications because of their excellent properties, e.g., high strength combined with low density [6,7].

Conventional high-strength Al-based alloys have been developed by precipitation hardening, grain refinement, dispersion strengthening, work hardening and fibre reinforcement [8]. The fracture strength of these Al alloys typically does not exceed 700 MPa. Furthermore, the strength of Al-rare earth metal (RE)–transition metal (TM) alloys with amorphous/nanocrystalline composite microstructures can reach as high as 1560 MPa [9]. Nevertheless, such high strength is only achieved in tensile tests of small pieces of ribbon samples because the amorphous or amorphous/nanocrystalline microstructures can be obtained only by melt spinning due to the poor GFA in Al–RE–TM systems [6,10]. Powder metallurgy (PM) is an alternative processing technique to fabricate large-size Al-based amorphous alloys/composites [7,11–13]. In addition, although Al-based nanocrystalline alloys/composites have been regarded as advanced materials with high strength and plasticity, nanocrystalline-grain Al alloys cannot be easily obtained due to the difficulty in controlling the growth of crystals during the solidification process. Crystallization from the amorphous state is a favourable option to fabricate Al alloys with ultrafine grains, and nanocrystallization can occur during the PM consolidation of amorphous powder precursors [14]. Recently, many attempts have been made to produce bulk-form samples that retain a nanocrystalline/amorphous or even nanocrystalline microstructure after the consolidation of rapidly solidified amorphous powders by extrusion and severe plastic deformation [11–13]. However, few studies have considered the underlying relationship between the sintering temperature (densification) and sample properties, such as strength and plasticity.

Because SPS is a consolidation technique that has the potential to achieve fast and full densification of nanostructured materials [15], in this paper, gas-atomized AlNiYLaCo partially amorphous powders were used to fabricate bulk nanocrystalline Al alloy samples by SPS. The obtained samples possess mainly nano-sized crystalline microstructures, which in turn leads to high strength and plasticity in compression.

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Table 1
Consolidation of the $Al_{86}Ni_7Y_{4.5}La_{1.5}Co_1$ alloy under various sintering conditions: parameters and results.

Temperature (T/°C)	Applied load (N/kN)	Duration (t/min)	Hardness (HV)	Density (ρ/g/cm^3)
250	9.4	1.5	193	3.02
300	9.4	1.5	259	3.19
350	9.4	1.5	258	3.27
400	9.4	1.5	245	3.34

2. Experimental methods

The Al-based alloy powders with a nominal composition of $Al_{86}Ni_7Y_{4.5}La_{1.5}Co_1$ (at.%) used in the present investigation were prepared by gas atomization. Prior to atomization, the alloy was synthesized in the inductively heated furnace of the atomizer under an Ar atmosphere using the pure elements Al, Ni, Y, La and Co. After complete melting of the pure elements, the melt was heated to approximately 1147 °C and then gas-atomized using Ar gas. The as-atomized powder was stored in air under ambient temperature and humidity. The powder particle size distribution was measured using a HORIBA LA-920 laser particle analyzer, and the measured D_{50} value was 34.9 μm.

The atomized $Al_{86}Ni_7Y_{4.5}La_{1.5}Co_1$ powder was consolidated using an SPS machine. The powders were placed into a 20-mm-diameter tungsten carbide die and sintered under vacuum at approximately 8.0×10^{-3} Pa for 1.5 min under various sintering conditions (see Table 1). The densities of the consolidated samples were measured by the Archimedes method, and the Vickers hardness was measured under an applied load of 500 g.

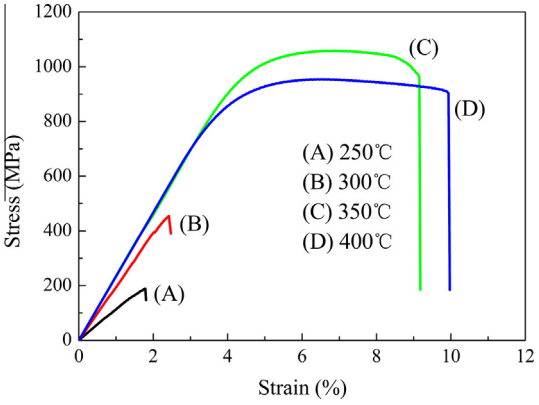

Fig. 2. Engineering stress–strain curves of the consolidated samples at various sintering temperatures.

The structural characteristics of powders and the obtained samples were investigated by X-ray diffraction (XRD, D/Max-Rb diffractometer, operated at 40 kV and 60 mA with Cu Kα), differential scanning calorimetry (DSC, Perkin–Elmer Pyris-I with a heating rate of 20 °C/min), scanning electron microscopy (SEM, FEI Company Quanta 200 FEG), and transmission electron microscopy (TEM, TecnaiG2F30). Compressive tests with cylinder samples of $\phi 2 \times 4$ mm were conducted with a strain rate of 4.0×10^{-4} s^{-1} using an Instron-5569 testing facility, and at least 4 samples were analysed to verify the reproducibility of the data. Fracture surfaces were also examined by SEM. TEM samples were prepared by grinding and then electro-polishing in a solution of 10% perchloric acid and 90% ethanol solution.

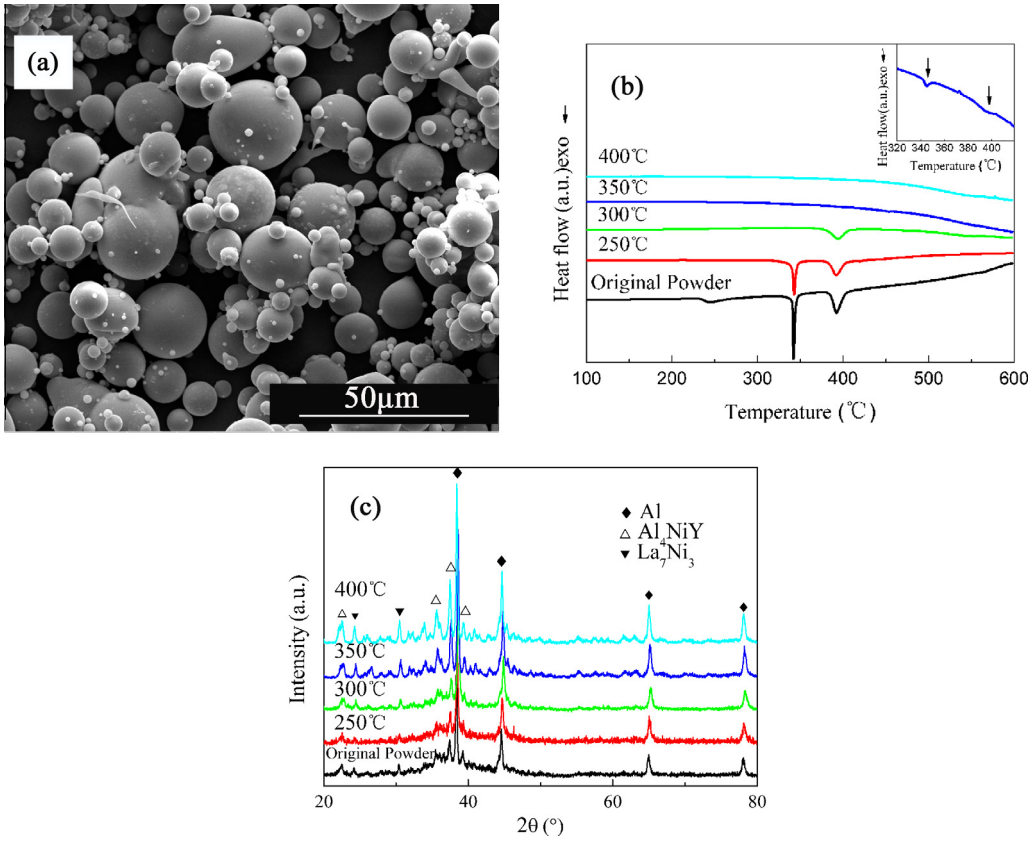

Fig. 1. SEM image of the gas-atomized powders (a). DSC curves (b) and XRD patterns (c) of the atomized powders and consolidated samples at various sintering temperatures. The inset of (b) shows an enlarged image of the DSC curve for the sample sintered at 350 °C.