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Aluminum powder size and microstructure effects on properties of boron nitride reinforced aluminum matrix composites fabricated by semi-solid powder metallurgy

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ABSTRACT

Al matrix composite reinforced by hexagonal boron nitride (h-BN) with nearly full densification was successfully fabricated by the semi-solid powder metallurgy technique. The h-BN/Al composites were synthesized with elemental pure Al powder size of d_{50}=35, 12 and 2 μm. The powder morphology and the structural characteristics of the composites were analyzed using X-ray diffraction, scanning and transmission electron microscopy. The density, Brinell hardness and compressive behavior of the samples were characterized. Density measurement of the Al composites revealed that the composite densification can be effectively promoted by plenty of embedded liquid phase under pressure. Composites prepared using Al powder with varying granularity showed different grain characteristics, and in situ recrystallization occurred inside the original grains with 35 μm Al powder. A sharp interface consisting of Al/Al_2O_3/h-BN was present in the composites. Both the compressive strength and the fracture strain of the investigated composites increased with the decrease of the Al powder size, along with the Brinell hardness. The composite with 2 μm Al powder exhibited the highest relative density (99.3%), Brinell harness (HB 128), compressive strength (763 MPa) and fracture strain (0.299).

1. Introduction

Al alloys and Al matrix composites produced by powder metallurgy (PM) have been receiving more attention than conventional melting-casting methods in aerospace, military and car industries, due to the improved physical, chemical and mechanical properties [1–3]. The large surface area of fine Al or Al alloy powders makes it possible to introduce naturally formed ultra-thin and dense surface oxides, which cannot be reduced to Al [4]. The oxide film will hinder metallurgical bonding between the powder particles and cause the formation of voids during the sintering process of the green compacts [5]. Thus, it is difficult to obtain fully dense Al alloys and Al matrix composites with clean and sharp interfaces. In particular, low wettability and inhomogeneous distribution of ceramic reinforcements are the main issues in the Al matrix composites (AMCs) preparation. Therefore, the worldwide effort has been to develop a short pressing-sintering process to obtain high performance Al alloys and Al matrix composites, similar to the iron-based products processing. To fabricate fully dense Al-based materials by powder metallurgy, conventional consolidation methods have been commonly used, including sintering and hot isostatic pressing (HIP) [6], extrusion [7], forging [8] and rolling [9]. These processes need large amounts of energy and have higher operating requirements. In recent years the semi-solid powder forging has been attracting an increased interest due to short processing and low energy consumption. Actually, the semi-solid powder forging is one kind of semi-solid powder processing [10], which combines the benefits of the semi-solid forming and powder metallurgy. In general, the semi-solid powder forging involves four basic steps: powder preparation, powder pre-compaction, heating and semi-solid forging. This technique has been successfully applied in processing alloy materials, such as Al6061 [10] and Al–Ti [11], and composite materials, including Al–SiC [12] and Al-CNT [13].

Hexagonal boron nitride (h-BN), also known as white graphite, has lamellar crystalline structure with excellent lubricating properties. Accordingly, h-BN is an important solid lubricant with numerous industrial applications. Moreover, it has key properties, such as high thermal conductivity, low thermal expansion, good thermal shock resistance, high electrical resistance, low dielectric constant and microwave transparency [14]. Additionally, h-BN has

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good neutron absorption ability and high workability. The h-BN is a light weight ceramic material with low theoretical density of only 2.25 g cm^{-3}, which is less dense than pure aluminum (2.7 g cm^{-3}) and common strengthening particles, such as SiC (3.22 g cm^{-3}) and Al_2O_3 (3.97 g cm^{-3}). Due to h-BN outstanding properties, it has been extensively investigated as ceramic dispersant in metals [15–19]. Hence, there is an important possible application of h-BN as the dispersed phase in AMCs with light weight and high performance. However, there still exists the crucial problem of poor bonding between the h-BN and the Al matrix. To overcome this problem, several manufacturing methods have been proposed, mainly including high energy ball milling [15] and pressureless infiltration [18].

In this investigation, elemental pure aluminum and copper powder were utilized to prepare h-BN reinforced Al–Cu matrix composites by the semi-solid powder forging. The aim of this paper was to evaluate the effects of aluminum powder size on the microstructure and mechanical properties of the as-forged h-BN/Al–Cu composites.

2. Experimental procedure

2.1. Material

Three different kinds of commercially available gas atomized Al powders with d_{50}=35 μm (Al > 99.8 wt%), d_{50}=12 μm (Al > 99.5 wt%) and d_{50}=2 μm (Al > 99 wt%) were used in this study. The powders were gas atomized and collected under nitrogen. Electrolytic copper powder with the size of d_{50}=45 μm (Cu > 99.9 wt%) was used as the starting material for the Cu alloy element. Commercially available h-BN powder (1–5 μm particle size, 99 wt% pure) was used as the reinforcement in the as-forged composites.

2.2. h-BN/Al composite fabrication

Three different kinds of Al powders, electrolytic copper powder and h-BN powder were used to make Al-5.3 wt% Cu-3 wt% h-BN composite and Al-5.3 wt% Cu alloy samples. The powder mixtures were low energy ball milled using steel jars and balls (10 mm, 8 mm, and 4 mm diameter). N-hexane was used as the process control agent to avoid particles agglomeration. The milling was performed for 5 h with a ball-to-powder weight ratio of 4:1. The rotation speed of the steel vials was set at 200 rpm. After milling, the powders were naturally air dried. The powder mixture was pre-compacted under 5 MPa pressure in the high purity graphite mold, which was then heated in a furnace with high purity argon as the protective atmosphere. 10 MPa pressure was slowly applied at 640 ± 2 °C, and the pressure was held constant for 60 min. The pressure was then unloaded and the samples were cooled with the furnace. A schematic of the manufacturing process is illustrated in Fig. 1. Once the samples cooled down, sections were removed for analysis and the remainder of the composite samples was subjected to the T6 heat treatment within 48 h of forming. Along with the Al-5.3 wt% Cu without h-BN, the formed materials were solutionized at 537 ± 2 °C for 10 h, quenched in water at room temperature and immediately artificially aged at 175 ± 2 °C for 5 h. Different kinds of prepared samples A–F are summarized in Table 1.

Table 1
The samples from different starting powders prepared by the liquid phase forging.

Sample	Starting powder				
	Al (d_{50}=35 μm)	Al (d_{50}=12 μm)	Al (d_{50}=2 μm)	Cu	h-BN
A	■	–	–	■	–
B	■	–	–	■	■
C	–	■	–	■	–
D	–	■	–	■	■
E	–	–	■	■	–
F	–	–	■	■	■

2.3. Characterization

The powder morphology and bulk samples' microstructure were analyzed using scanning electron microscopy (SEM, LEO-1450). Energy dispersive spectrometry (EDS) was used to assist the SEM analysis. The interface between the h-BN and the Al matrix was carefully observed and analyzed using transmission electron microscopy (TEM, Tecnai G2 F30). Phase analysis of the composite and alloy samples was carried out by X-ray diffraction (XRD, Rigaku TTR III) using monochromatic Cu Kα radiation with the X-ray wavelength of 0.154 nm, operated at 40 kV and 150 mA. The hardness values of the samples were determined using the Brinell hardness tester (HB, DHB-3000, China) with 5 mm cemented carbide ball indenter, 2.5 kN load and the 30 s loading time. For each test, at least three specimens were tested to obtain the average hardness values. The standard deviation of the hardness measurements is 1.2 HB. The density of the as-forged materials was measured using the Archimedes' principle.

3. Results and discussion

3.1. Powders characterization

The representative morphology of the as-atomized Al powder and milled powder used in this work is shown in Fig. 2. Three

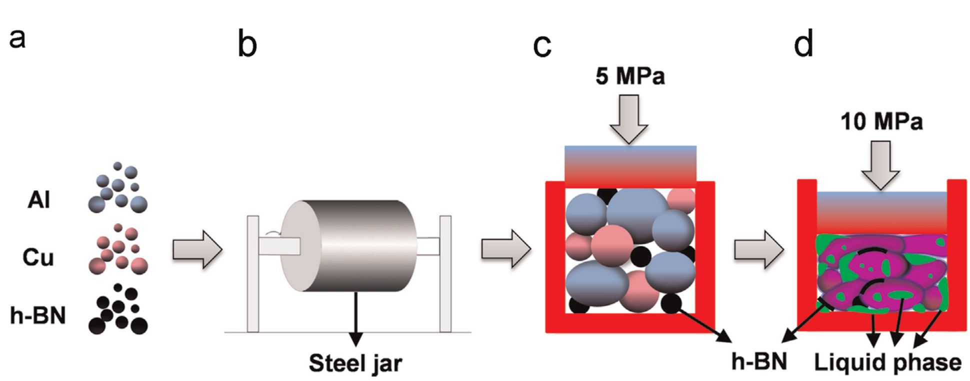

Fig. 1. Schematic drawing of the manufacturing process: (a) raw powders; (b) powder mixture by ball milling; (c) powder compact at room temperature under 5 MPa pressure; (d) densification of the powder compact at 640 °C under 10 MPa pressure.