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Original Research Paper

Morphological and structural studies on Al reinforced by Al_2O_3 via mechanical alloying

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ABSTRACT

In the present work, aluminum matrix composite (Al–Al_2O_3) was produced using mechanical alloying in a planetary ball mill. Aluminum granular in size (1–3 mm) with high amount of alumina particles (x_{50} = 7.6 μm) were milled up to 500 minutes in a planetary ball mill to indicate the effect of hard particles on the alloying acceleration. The results revealed that high amount of alumina particles promoted the work hardening and decreased the time of mechanical alloying. Further, the particle size analysis indicated that prolonging the milling time caused the particle size to drop from an initial value of 1–3 mm to about 10 μm during the milling. The X-ray diffraction results demonstrated a continuous decrease in crystallite size in Al phase from 350 to 60 nm. Hardness tests illustrated that hardness increased as a function of milling time. The results verified that the produced composites have a homogeneous distribution of alumina particles in the aluminum matrix. The results showed that the aluminum matrix composite can be produced from the granular Al (mm in size) with micron sized Al_2O_3 by mechanical alloying process.

1. Introduction

As metal matrix composites, aluminum matrix composites (AMCs) are produced by adding a ceramic material (reinforcement) to aluminum matrix [1–4]. Alumina is known as a suitable reinforcement for the Al matrix. It is chemically inert with Al and can be used at higher temperatures and has the benefit of resistance to creep [5]. AMCs have higher strength [2], higher ratio of stiffness to density [3], and also better fatigue and wear resistance than does unreinforced Al [4,6]. AMCs therefore, generally appeal to e.g. automotive, defense and aerospace industries [7].

It is possible to manufacture such composites by powder metallurgy (PM) with homogeneous distribution of the reinforcement particles at both micro and nano scales [7]. Such distribution of reinforcements and prevention from typical segregation of reinforcements (typically taking place during casting method) are two main advantages of PM in comparison with other methods of composite production [7].

In 1978, as a first investigation, Benjamin used mechanical alloying (MA) as a PM technique to produce nickel based super alloy composite [8]. This method was later widely used to produce all types of alloys such as shape memory alloys [9], amorphous alloys [10], stainless steel [11], and aluminum alloys [12].

In some investigations, MA technique has been used to produce aluminum matrix composites (AMCs) [4,5]. MA process typically consists of a repeated welding-fracture and re-welding of powder particles in a high energy ball mill. The principle of this process is trapping particles between colliding balls which leads to a continuously repeated plastic deformation and/or fracture [8]. The whole process of MA is well visualized by the model of Fogagnolo et al. [13]. This model is based on the hardness of primary particles (Fig. 1).

According to Fogagnolo model [13] there are three different stages during MA; deformation, fracturing and cold welding. In the first stage, during the milling the morphology of Al particles deforms and changes to flaky shape, while the Al_2O_3 particles are milled. The milled Al_2O_3 are placed between the flaky ductile Al (Fig. 1). Finally, the cold welding leads to production of composite particles (Fig. 1). The cold welding as a dominant mechanism changes the morphology of the composite particles (due to piling up of the laminar particles). In the next step, agglomerated particles become hardened, and this effect lead to the domination of fracture mechanism. At the end of process, the fracturing and cold welding reach their equilibrium and composite particles are formed with equiaxed morphology.

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The quality of AMCs depends on many factors such as amount of reinforcement, size of reinforcement and time-span of the manufacturing process. Several studies suggested that even a small amount (up to 5 wt.%) of reinforcements leads to significant improvement of the composite properties [7,14–16]. Also some researchers reported that the higher amount of reinforcements (up to 20 wt.%) leads to homogeneous distribution of ceramic particles [17,18].

However increasing the amount of reinforcement is not trivial. During the MA process a part of energy is required to grind the primary materials. Larger particles require a higher energy to grind [8]. This fact eventually increases the time-span of the process and introduces additional heat to the system [8]. The additional heat is critical in the process since the Al powder is a highly reactive metal and its oxidation is extremely prone to explosion [19].

Although the particle size effect on the MA is considerable, it has not been comprehensively studied. Therefore, to address these concerns, in this study, the effect of granular Al particles (1–3 mm) and micro size Al_2O_3 powder (7.6 µm) is investigated. To the authors' knowledge, it is the first record of understanding the size effect on manufacturing AMCs.

This work describes the influence of different Al_2O_3 fractions on the MA process. The effect of large Al particles and various amount of Al_2O_3 powder on the time-span of MA is also studied. The results can be used to better understand the effect of milling on the Al particles and AMCs with high amount of Al_2O_3 during MA.

2. Experimental procedure

The granular Al particles and Al_2O_3 powder were used to produce the aluminum matrix composite. Table 1 presents the characteristics of primary materials. Al particles (supplied by Hösch GmbH, Germany) were almost spherical with approximate size 1–3 mm and Al_2O_3 powder with size of 7.6 µm were used as reinforcements. The particle size and morphology of Al particles were determined by a laser particle size analyzer (HELOS, Sympatec GmbH-Germany) and a scanning electron microscopy (SEM) (Phonom GmbH, Germany), respectively. The SEM micrographs of primary particles are presented in Fig. 2.

The mechanical alloying was performed in a planetary ball mill (pulverisette 5 classic – Fritsch GmbH, Germany) with four stainless steel grinding jars (250 ml) and balls (12 mm in diameter).

Table 1
Characteristics of the starting materials.

Material	Size	Particle shape	Purity
Al	1–3 mm	Semi-spherical	>99%
Al_2O_3	$x_{50} = 7.6$ µm	Irregular	>99%

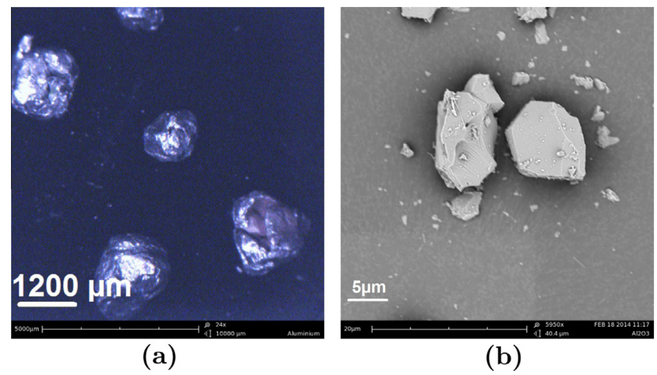

Fig. 2. (a) Optical image of Al and (b) SEM micrograph of Al_2O_3 as primary powders.

The MA conditions employed were: milling speed 240 rpm, 10:1 balls to powder ratio (by wt.%) with a 2–4 wt.% of methanol (Carl Roth GmbH, Germany) as a process control agent to prevent excessive cold welding. To avoid the oxidation and contamination during MA, the milling process was done in argon atmosphere.

The Al particles were mixed with 25, 33 and 50 wt.% Al_2O_3 and mechanically milled up to 500 min. Al particles without addition of Al_2O_3 were also processed at the same conditions to study the role of the reinforcement particles on the mechanical milling stages. The effect of milling time on the process was studied in composite with 33 wt.% Al_2O_3 (during 180, 240, 300, 360, 420, and 500 min).

The particle size distribution (PSD) of the milled powders was determined using a laser particle size analyzer. The morphology evolution of the powders during milling was studied by SEM. The XRD was employed to determine the real structure of samples and lattice strain of the powders. An URD6 diffractometer (Seifert, FPM, Freiberg, Germany) with $CuK\alpha$ radiation ($\lambda = 0.15418$ nm) was used. The diffraction patterns were recorded in angular

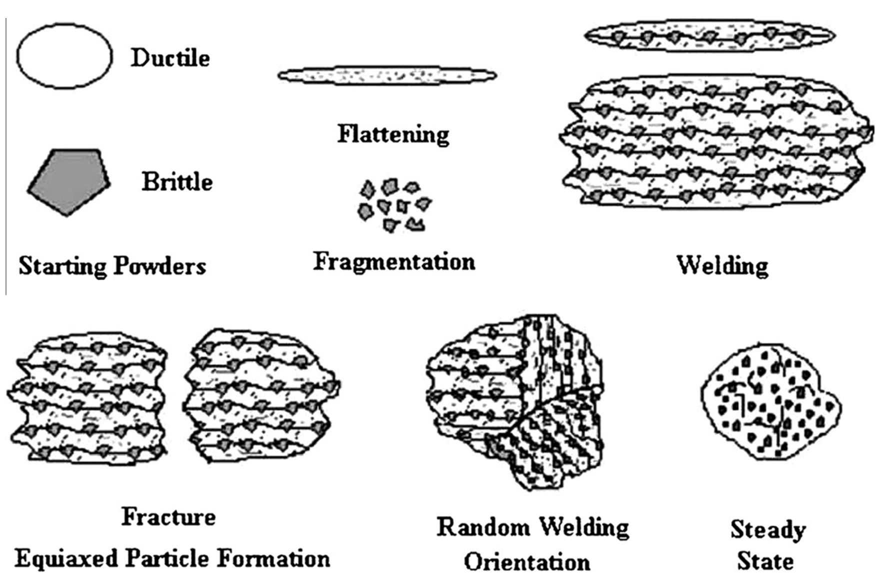

Fig. 1. Schematic of mechanical alloying process at a ductile–brittle system [13].