Materials Science & Engineering A 560 (2013) 567–574

Contents lists available at SciVerse ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

Application of powder metallurgy and hot rolling processes for manufacturing aluminum/alumina composite strips

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A R T I C L E I N F O

Article history:
Received 4 September 2012
Received in revised form
27 September 2012
Accepted 28 September 2012
Available online 6 October 2012

Keywords:
Powder metallurgy
Mechanical alloying
Vacuum hot pressing
Hot rolling
Mechanical properties

A B S T R A C T

In this study, aluminum matrix composites (AMC) with 2, 4, 6 and 10 wt% alumina were produced using powder metallurgy (PM), mechanical milling (MM) and vacuum hot pressing (VHP) techniques; then, this was followed by the hot-rolling process. During hot rolling, AMCs with 6 and 10 wt% Al_2O_3 were fractured whereas strip composites with 2 and 4 wt% Al_2O_3 were produced successfully. Microstructure and mechanical properties of the samples were investigated by optical and scanning electron microscopes and tensile and hardness tests, respectively. Microscopic evaluations of the hot-rolled composites showed a uniform distribution of alumina particles in the aluminum matrix. It was found that with increasing alumina content in the matrix, tensile strength (TS) and hardness increased and the percentage of elongation also decreased. Scanning electron microscope (SEM) was used to investigate aluminum/alumina interfaces and fracture surfaces of the hot rolled specimens after tensile test. SEM observations demonstrated that the failure mode in the hot-rolled Al-2 wt% Al_2O_3 composite strips is a typical ductile fracture, while the failure mode was shear ductile fracture with more flat surfaces in Al-4 wt% Al_2O_3 strips.

1. Introduction

Improvement of aluminum alloys properties can be achieved by various methods such as new alloy design, heat treatment or reinforcement with other types of material to produce metal matrix composites (MMCs) [1]. Particulate reinforced aluminum composites have specific properties such as lightweight, high specific strength and normal fabrication expense. Combination of these properties is not available in most conventional materials. Consequently, they have a great potential of application in defense and automotive industries [2]. A large number of different oxides, carbides, nitrides and borides are suitable for reinforcement. AMCs can be made highly resistant by adding spread out, hard, and brittle particles such as Al_2O_3, TiC, SiC and etc. [3,4].

A wide range of production techniques have been developed for aluminum matrix composites, such as the accumulative roll bonding (ARB) method [5], anodizing and ARB processes [6], stir and compo-casting procedures [7] and also, by PM. Among others; however, the PM method is the most attractive due to several reasons. PM process offers some benefits not found in ingot metallurgy or diffusion welding. The most important benefit is the low manufacturing temperature that prevents strong interfacial reactions, deduces the undesirable reinforcement/matrix reactions and also, ensures uniform distribution of reinforcement particles in the matrix as compared with other MMCs production methods [8,9].

Mechanical milling of a blend of ceramic powder and metal powder is generally used to get the best mechanical properties in aluminum/alumina composites. A number of authors have investigated the microstructure and mechanical properties of aluminum/alumina composites. Zebarjad and Sajjadi [10,11] investigated microstructure evaluation of Al/Al_2O_3 composites after mechanical alloying as well as the relation between physical and mechanical properties of this composite with milling time. Severe plastic deformation of particles by high energy ball milling force can cause grain size refining and internal stress concentration [12]. Razavi-Tousi et al. [13] produced Al-20 wt%Al_2O_3 composite by mechanical milling and examined microscopic evolution of samples. In recent years, VHP of powders, the well-known and least complicated powder consolidation method has been employed. So in this research, uniaxial vacuum hot pressing technique was used to produce initial composite samples.

Accomplishing plastic deformation process such as rolling on MMCs improves mechanical properties such as strength and ductility [14,15]. At high temperatures, materials have a malleable, paste-like and easily formable consistency, allowing a high amount of deformation without work hardening of the material [16].

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0921-5093/$ - see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.msea.2012.09.103

Heidarpour and Shafyei [17] studied the effect of hot rolling process on mechanical properties of Al–SiC composite and illustrated that the redistribution of reinforcement particles after rolling increased hardness of samples due to grain structure refinement. Pal et al. [18] investigated room temperature mechanical properties and tensile creep behavior of powder metallurgy processed and hot rolled Al and its composites with different vol% SiC particulate reinforcements. They found that the increase in volume fraction of SiC resulted in a smooth increase in Young's modulus, yield and ultimate tensile strengths.

The aim of this work is to produce the high strength and highly uniform Al–Al_2O_3 composite strips using powder metallurgy and hot rolling processes and to investigate their microstructure, mechanical properties and fracture behavior.

2. Experimental procedures

2.1. Materials

As received commercial aluminum powders with ~93.8% purity, and particle size <40 μm and also, Al_2O_3 powders with 3–8 μm particle size with polyhedral shape were used. The chemical composition of aluminum powders is shown in Table 1. Alumina powders specifications are also given in Table 2.

2.2. Mechanical milling

Aluminum powder was mixed with 2, 4, 6 and 10 wt% of Al_2O_3 in a high energy planetary ball mill with 400 rpm for 300 min. In this process, ten balls made of hardened tool steel with different sizes (4.20–12.28 mm in diameter) were used. Mechanical milling was taken under argon gas control. The ratio of ball to powder was 10:1 and stearic acid [19] was used as a process control agent (PCA) material with a proportion of 0.8–1 wt% of total powders.

2.3. Vacuum hot pressing

Samples were pressed at an initial pressure of 100 MPa and then hot pressed at 200 MPa in a graphite die with 45 mm diameters and 20 mm height. The compressed powders were then sintered at 773 K for 45 min under vacuum condition. Fig. 1 shows the schematic view of hot pressing equipment. During the pressing procedure, much lubricant material is needed. Graphite emulsion was used as a lubricate material for die wall and bottom of punch because there is a tendency for abrasion and blistering in aluminum powders. Finally, the specimens were cooled gradually in air.

2.4. Specimens preparation

After sintering in a vacuum hot press die, specimens were cut perpendicular to the compression axis by a computer numerically controlled (CNC) wirecut machine. Thickness of each slice was 10 mm. The schematic view of specimens can be seen in Fig. 2.

2.5. Hot rolling

Hot rolling experiment of slices was performed using a laboratory rolling mill with a loading capacity of 20 t. In order to deduce friction, rolls were soaked by incombustible grease. Samples were heated at 723 K for 6 min in a cylindrical resistance furnace for each cycle of hot rolling. The rolling speed in this work was chosen to be 4.2 m/min. To obtain a uniform distribution of alumina particles in the matrix and remove microvoids and porosities in the interfaces of aluminum/aluminum and aluminum/alumina particles, the aforesaid process was further repeated so that the final thickness of strips reached to 1 mm.

2.6. Investigation of mechanical properties

Brinell hardness measurements of the samples were performed under a load of 31.25 kgf and $F/D^2=5$, where F is the load, and D is the diameter of ball, corresponding to ASTM E 10-84 [20]. For each

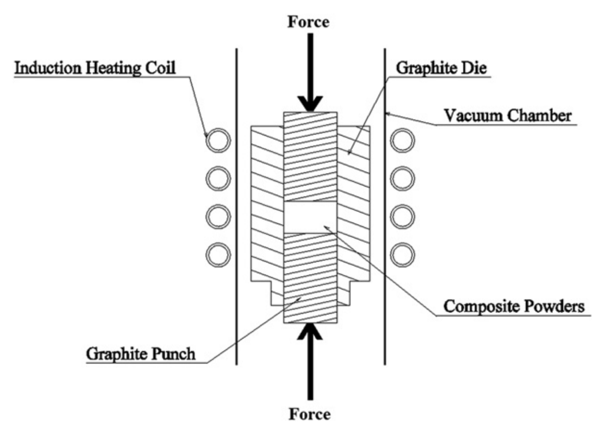

Fig. 1. Schematic view of hot pressing equipment.

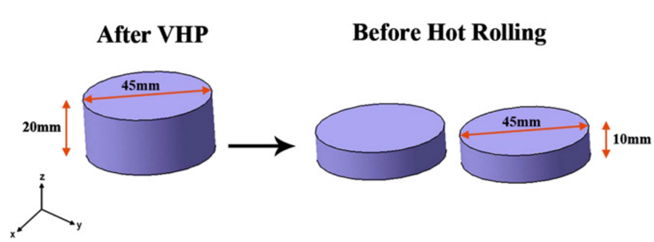

Fig. 2. Schematic view of slices after VHP.

Table 1
Chemical composition of aluminum powders from EDS analysis.

Element	Line	Intensity (c/s)	Error 2-sig	Conclusion	Units	Voltage=20.0 KV Take off angle 35°
Al	Ka	980.20	6.710	93.789	wt%	
P	Ka	3.00	0.680	0.659	wt%	
Ag	La	6.99	0.814	4.145	wt%	
Te	La	1.86	0.627	1.406	wt%	
				100.000	wt%	Total

Table 2
Alumina powders specifications for the reinforcement of metals [4].

Average particle size	Type of crystal	Melting point (°C)	Young's modulus (GPa)	Density (g cm^{-3})	Heat conductivity (Wm^{-1} K^{-1})	Mohs-hardness	Thermal coefficient of expansion (10^{-6} K^{-1})
3–8 μm	Hexagonal	2050	410	3.9	25	6.5	8.3