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Review

Mechanical and microstructural characterization of aluminum reinforced with carbon-coated silver nanoparticles

R. Martínez-Sánchez [a,*], J. Reyes-Gasga [c], R. Caudillo [b], D.I. García-Gutierrez [b], A. Márquez-Lucero [a], I. Estrada-Guel [a], D.C. Mendoza-Ruiz [a], M. José Yacaman [b]

[a] *Centro de Investigación en Materiales Avanzados (CIMAV), Miguel de Cervantes No. 120, CP 31109, Chihuahua, Mexico*
[b] *Texas Materials Institute and Chemical Engineering Department, University of Texas at Austin, Austin, TX 78712-1063, USA*
[c] *Instituto de Física, UNAM, Apartado Postal 20-364, 01000 México, D.F., Mexico*

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Abstract

Composites of pure aluminum with carbon-coated silver nanoparticles (Ag-C NP) of 10 nm in size were prepared by the mechanical milling process. Transmission electron microscopy showed that the Ag-C NP are homogeneously dispersed into the Al matrix, silver nanoparticles do not coalesce, grow or dissolve in the aluminum matrix due the carbon shell. The values of yield strength (σ_y), maximum strength (σ_{max}) and microhardness Vickers (HVN) of the composites were evaluated and reported as a function of Ag-C NP content. It has been found that the introduction of this type of particles in aluminum strengthen it, increasing all the previous parameters.

Keywords: Composites materials; Powder metallurgy; Mechanical properties; Transmission electron microscopy (TEM)

Contents

1. Introduction

Aluminum alloys have a wide variety of industrial applications because of their low density and good workability, but their use is limited by their relatively low yield strength. The need to increase aluminum strength for applications in the aerospace and aeronautics industries has motivated the study of aluminum matrix composites. Recently, a number of composites have presented excellent mechanical properties at both, medium (473 K) and room temperatures [1,2]. It is well known now that aluminum, aluminum alloys, and aluminum composites can be strengthened by dispersing hard particles such as carbides, oxides or nitrides into the aluminum matrix by using different techniques in the solid or liquid state [3,4].

In particular aluminum composites can be prepared in the solid state by powder metallurgy (PM), which additionally presents versatility and lower production costs. This type of composite production process involves the mixing of reinforcement particles with the metallic powder, followed by consolidation and sintering processes. Other methods also include mechanical alloying (MA) and mechanical milling (MM), which renders composites with fine and homogeneous

* Corresponding author. Tel.: +52 614 439 11 46.
E-mail address: roberto.martinez@cimav.edu.mx (R. Martínez-Sánchez).

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distributions of the particles [5–7]. Several works about aluminum-second phase particles had been reported [8–12], some of them are related with commercial Al–Mg–Si alloys, but containing coarse particles (tenths of microns) [8,9]. Additionally, some of them conclude that nanometer sized particles dispersed into aluminum alloys can be dissolved by heat treatment and/or by applying high deformations [10–12].

Recently, a new nanometric compound has been developed. This compound consists of nanometric particles of silver coated with carbon dispersed into aluminum matrix. These particles are stable and easy to handle. As the nanometric carbon layers are attached to the silver particles they are not dissolved into Al matrix, and can be easily dispersed in it. In the present work we employed for the first time this type of particles to reinforce an aluminum matrix.

The focus of this work is the microstructural and mechanical characterization on an Al-based composite produced by dispersion of silver nanoparticles coated with carbon. Microstructural analysis on Al matrix and dispersed silver nanoparticles is presented; additionally, an analysis of the silver nanoparticles effect in mechanical properties is shown.

2. Experimental procedure

The raw powder materials used were Al (99.5% purity, −200 meshes in size) and carbon-coated silver nanoparticles with an average size of ∼10 nm (Fig. 1), hereafter refered as "Ag-C NP". The Ag-C NP, is a product obtained from Nanotechnologies, Inc. (Austin, TX), which is produced by arc discharge and stabilized with carbon from a hydrocarbon source. Aluminum-based composites with content of 0.0, 0.25, 0.50, 0.75, and 1.0 wt.% Ag-C NP were made by mixing followed mechanical milling in a high energy SIMOLOYER mill for 2 h under argon atmosphere. The milling ball-to-powder weight ratio was set at 20–1. The total sample weight was 50 g. Because of the short milling times set, no process control agent was used.

Consolidated bulk products (40 mm in diameter Ø) were prepared by pressing the milled powder at ∼950 MPa for two minutes under uniaxial load. Compacted samples were sintered for 3 h at 823 K under high vacuum with a heating rate of 50 °C/min. Sintered products were held for 0.5 h at 823 K and hot extruded into a rod of 10 mm diameter by using indirect extrusion and an extrusion ratio of 16. Compression test was carried out in an INSTRON testing equipment at room temperature and at constant displacement rate of 0.016 mm/s. The yield strength was measured at the elastic limit. The height-to-diameter ratios h:Ø of 0.8 and 2.0 were used in accordance with the ASTM E9 standard. The structural analysis was done by transmission electron microscopy (TEM) using the techniques of high resolution (HRTEM), scanning transmission electron microscopy (STEM) and the chemical analysis by characteristic X-ray energy dispersion spectroscopy (EDS). For TEM observations 3 mm in diameter foils were obtained from extruded products. Polished sections and thin foils samples were prepared by electro-polishing using a STRUERS TENOPOL-3 equipment, and a 26% by volume nitric acid in methanol mixture at 248 K and 20 V CD. A HRTEM JEOL 2010F microscope with STEM unit and a resolution of 0.19 nm was used. This microscope is also equipped with an OXFORD-INCA EDS. The Digital Micrograph (GATAN) software was used to record the images.

3. Results

Fig. 1 shows representative SEM (a) and TEM (b) images of the Ag-C NP in the as-received condition. Notice in Fig. 1b the nano-size of the particles and the gray contrast that surrounds the silver nanoparticles, which correspond to carbon. Fig. 2 shows conventional TEM bright field images of the Al sample with 1% of Ag-C NP. The contrast corresponds to bend contours, grain boundaries and dislocations.

As part of the contrast, there is also a continuous distribution of dark spots. A detailed analysis of these dark spots indicates that there are particles in the range of 100 nm and others one in the range of ∼10 nm. Fig. 3a illustrates the form of the bigger ones, which were identified, employing an EDS analysis, as Fe particles (Fig. 3b–d) probably arising from the milling device wear; while those with ∼10 nm ones correspond to the Ag-C NP particles (Fig. 4a and b).

Fig. 5 shows the high resolution TEM images (HRTEM) of the Ag particles. This type of particles has been analyzed in our laboratory, and it corresponds to the icosahedral and decahedral shaped particles [13,14]. Observe also, in these images, the gray contrast that surrounds the particles. The crystalline lines observed in the matrix correspond to the Al lattice. Evidence that Ag-C NP is still covered with a carbon shell is presented in Fig. 6a–d. In these figures, the images of carbon EDS mapping convincingly proves that carbon surrounds the Ag nanoparticles, as they already were before their dispersion into the Al matrix (Fig. 1), and the carbon shell present an homogeneous thickness (Fig. 6c and d). This is an indication that the carbon shell prevents the nanoparticles from coalescence and/or their diffusion into aluminum matrix.

Therefore, the samples consisted of some Fe particles of approximately 100 nm in size, produced during the MM process, together with Ag particles, introduced by design, of

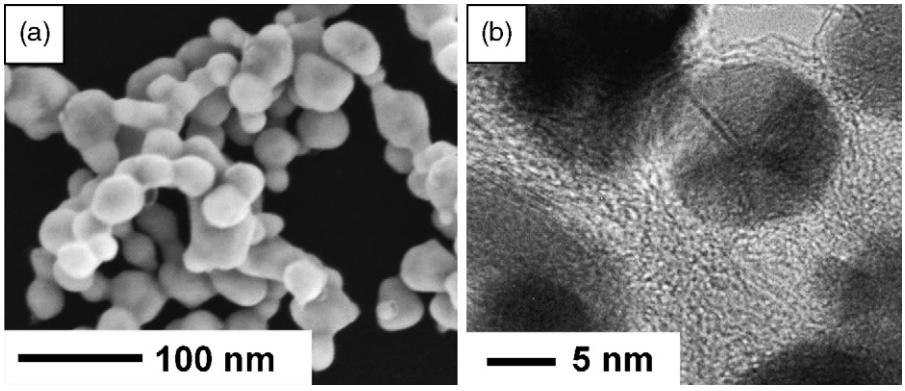

Fig. 1. Ag-C NP before processing: (a) SEM image and (b) HRTEM image. The carbon layer covering the particles is clearly observed in (b).