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Foam behavior of solid glass spheres – Zn22Al2Cu composites under compression stresses

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ABSTRACT

Solid glass spheres – Zn22Al2Cu composites, having different densities and microstructures, were elaborated and studied under compression. Their elaboration process involves alloy melting, spheres submersion into the liquid alloy and finally air cooling. The achieved composites with densities 2.6884, 2.7936 and 3.1219 g/cm^3 were studied in casting and thermally induced, fine-grain matrix microstructures. Test samples of the composites were compressed at a $10^{-3}\,s^{-1}$ strain rate, and their microstructure characterized before and after compression by using optical and scanning electron microscopes. Although they exhibit different compression behavior depending on their density and microstructure, all of them show an elastic region at low strains, reach their maximum stress (σ_{max}) at hundreds of MPa before the stress fall or collapse up to a lowest yield point (LYP), followed by an important plastic deformation at nearly constant stress (σ_p): beyond this plateau, an extra deformation can be limitedly reached only by a significant stress increase. This behavior under compression stresses is similar to that reported for metal foams, being the composites with fine microstructure which nearest behave to metal foams under this pattern. Nevertheless, the relative values of the elastic modulus, and maximum and plateau stresses do not follow the Ashby equations by changing the relative density. Generally, the studied composites behave as foams under compression, except for their peculiar parameters values (σ_{max}, LYP, and σ_p).

1. Introduction

Alloys rich in Zn have been investigated extensively in recent years [1–7]. It is well know that Zn, as a pure element, has very limited properties for industrial applications, whereas Al-based alloys like Zn22Al, Zn27Al and Zn4.6Al with small quantities of Cu, Mg or Ag have attracted the researchers attention because their surprising superplastic property [8–12], when they have a fine-grained microstructure and are deformed under a quasi-static rate. Basic studies are also of interest, because of the strong dependence between microstructure and properties, varying, for example, the type and/or quantities of alloying elements, or the elaboration process like thermal, mechanical, or thermo-mechanical [13–17]. For example, ZnAlCu alloys are normally synthesized by the conventional casting process because it is easy, fast and economical; however the resulting microstructure presents some defects that limit its application under compression.

On the other hand, Zn22Al and Zn27Al alloys have found further applications as foams (or sponges) and composites. In general, this kind of materials can exhibit attractive properties [18–20], for example, high mechanical resistance at low density, super-plasticity, etc. Moreover, metal matrix composites have good wear resistance and as metallic foams or sponges are good energy absorbers. Some metal matrix composites (MMC) based on Zn22Al alloy have been synthesized with several structural components like whiskers or particles of SiC [21–25], Al_2O_3 [26], ZnO [27], graphite [28], hydroxyapatite [29] and $CuZn_5$, $CuZn_2$, $CuAl_2$ [30]. Interesting here is the reported mechanical behavior under compression or tensile stresses, applied at different strain rates to evaluate super-plasticity or damping conducts by measuring internal friction. All these new properties make them very interesting for engineering applications.

Hitherto, metallic foams based on Zn22Al alloy have been prepared by different procedures. For example, the eutectoid composition Zn22Al alloy was produced as foam, using the melt foaming method with $CaCO_3$ [31,32] or titanium hydride (TiH_2) [33] as blowing agent, and adding short Al_2O_3 fibers [34] or SiC [35,36] as reinforcement and

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stabilizing agents. Also, foams of Zn22Al with open-cells [37] and Zn22Al–1Cu having different microstructures [38], induced by heat treatment, have been elaborated by a replication process of NaCl preforms to study the compressive behavior and energy absorption capacity. The first work on closed-cells Zn–22Al foams elaborated by the powder metallurgy technique was also performed corroborating its strain rate sensitivity [39]. Moreover, a novel Zn22Al syntactic foam composite was reached via stir casting (vortex), with different volume fractions (6–50 vol%) of Ni-coated fly ash micro-balloons as foaming agent. The effect of the fly ash volume fraction on the microstructure, compressive behavior and sensitivity to the strain rate were determined [40].

No research has been reported before about the preparation and characterization of composites based on Zn22Al eutectoid alloy, having solid glass spheres as the structural component. Therefore, it would be interesting to study their mechanical behavior under compression in order to improve this property.

In this work it is reported the microstructural characterization and compressive behavior of an original composite with three different densities, formed by solid glass spheres in Zn22Al2Cu matrix alloy with two different microstructures. One of them, the original casting microstructure with its well-known structural defects, and the other one, the thermally induced fine microstructure, with superplastic property. At this point, it is interesting to study the influence of the glass spheres, as structural component, in the mechanical properties of both kind of microstructure in matrix.

The composites were prepared by an innovative method and tested under compressive stresses at a quasi-static strain rate. They behave in general like solid foams. Their compression behavior changes with the matrix microstructure and the composite density, but they do not follow the Ashby equations for the foams. However, they reach higher maximum stresses by lower densities than conventional foams or syntactic foams with similar matrixes.

2. Background

2.1. Composites

The density of a composite can be calculated from the densities and volume fractions of its individual components according to the mixtures rule equation:

$$\rho_c = \rho_s X_s + \rho_m X_m \tag{1}$$

where ρ is the density, c the composite, s the structural component, m the matrix, and X the volume fraction.

It is known that the elastic modulus (E) of any particulate composite lies between two limit values, named upper, E_{UL}, and lower, E_{LL}, limits. They can be calculated by the following equations:

$$E_{UL} = X_s E_s + (1 - X_s) E_m \tag{2}$$

$$E_{LL} = 1/[X_s/E_s + (1 - X_s)/E_m] \tag{3}$$

Eqs. (2) and (3) are the direct and inverse mixture rules inferred for elastic modulus of long fibers composites with strain applied towards a parallel and perpendicular direction with respect to the fibers, respectively [19].

2.2. Foams

Relative elastic modulus of foams to matrix, E_f/E_m, has been reported [41] to follow a quadratic or cubic behavior with respect to the corresponding relative densities, ρ_f/ρ_m, as long as the foams have open or closed cells, correspondingly:

$$E_f/E_m = C_1(\rho_f/\rho_m)^a \tag{4}$$

Here C_1 is a constant, $a=2$ for open cells and $a=3$ for closed cells.

Similarly, it has been found that the collapse stress and plateau stress of foams relative to yield stress of matrix, σ_{col}/σ_{ym} and σ_p/σ_{ym}, respectively, vary with the relative density, ρ_c/ρ_m, according to the Ashby equations [41]:

$$\sigma_{col}/\sigma_{ym}, \quad \sigma_p/\sigma_{ym} = C_2(\rho_c/\rho_m)^{3/2} \tag{5}$$

Here C_2 is a constant.

3. Material and methods

3.1. Alloy preparation

99.99% Zn, 99.27% Al and 99.999% Cu ingots were employed to prepare Zn22Al2Cu alloy by conventional casting in a crucible introduced in a muffle furnace previously heated at 700 °C. The mass of each component was measured using a precision balance (10^{-4} g), Mettler H45. The alloy density was determined by Archimedes method as 5.4 g/cm^3.

3.2. Composites elaboration

The raw materials used in this work were Zn22Al2Cu (Zinalco) alloy and solid spheres of borosilicate glass. Mariefeld manufacturing spheres of 4 mm diameter were selected with the following characteristics: melting point at 1100 °C, Young modulus between 78 and 85 GPa, density of 2.5 g/cm^3 and a chemical composition of 61–67% SiO_2, 10–18% Na_2O, 5–10% CaO, 3–8% Al_2O_3, 1–5% B_2O_3 and 0.5–3% MgO.

Composites elaboration was carried out using a three steps process: first, melting the alloy at 700 °C and heating the solid glass spheres at 400 °C, separately; second, introducing the preheated spheres into the molten alloy; third, slowly cooling the mixture in air. Flotation of spheres was avoided by pushing them with a cylindrical bar until the mixture viscosity was enough to retain them during the cooling. Fig. 1 shows the resulting glass spheres distribution into the matrix alloy.

To obtain composites of different densities, a constant alloy mass of 890 g was employed with 243.3, 300 and 400 g of structural component.

3.3. Density determination

A mass/volume ratio method was used to determine the composites density. For that, samples in parallelepiped form of

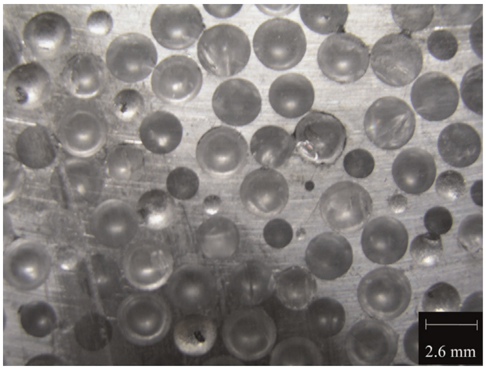

Fig. 1. Optical image showing the solid glass spheres distribution into the matrix alloy, forming the composite. In this case with density of 2.6884 g/cm^3.