Microstructure and Mechanical Properties of Cellular Magnesium Matrix Composites

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Abstract

The cellular solids prepared in the present study consist of a magnesium alloy matrix containing a high volume fraction of thin walled hollow alumina spheres. These so-called syntactic Mg/Al_2O_3 foams exhibit closed cells of homogeneous morphology.

Dynamic measurements of the elastic modulus and deformation tests in compression gave specific stiffnesses and strengths which are superior to currently available aluminum foams, whereas the absolute value of density is somewhat higher.

Using different Mg-alloys the effect of matrix strength on the compressive strength of syntactic magnesium foams was investigated. Foams with randomly packed and hexagonal close-packed hollow spheres were studied. The influence of the hollow sphere morphology, characterized by the ratio between sphere diameter and wall thickness, has been examined. It emerged that both matrix strength and sphere strength significantly contribute to the overall strength of the syntactic foams.

A physical model is proposed to rationalize the measured compressive strength. It is based on the rule of mixtures and takes into account the minimum load carrying cross sectional area. A good agreement with the experiments is reached.

1   Introduction

There is a wide range of methods to fabricate porous metallic structures [1]. The method employed in the present paper utilizes a second phase which is introduced into a matrix in form of hollow spheres, leading to a closed cell composite structure, which has also been termed "syntactic foam". Such foams can be produced by liquid metal infiltration of hollow ceramic sphere arrays. The technique has been applied to aluminum [2, 3] and to titanium [4] matrices. Recently, low density syntactic metal foams have been developed using magnesium, the lightest commonly used structural metal, as the matrix component [5, 6]. They will be called cellular magnesium matrix composites (CMMCs) in the following.

The subject of this study is to describe the microstructure and the mechanical properties of CMMCs that are very promising for weight saving applications. Moreover, a simple physical model for the compressive strength of CMMCs is presented which is able to rationalize the correlation between the mechanical properties and the volume fraction, wall thickness and stacking order of the hollow spheres.

2   Experimental Procedure

The materials investigated in this study consist of different magnesium alloy matrices (cp-Mg, AM20, AM50, AZ91), containing hollow alumina spheres with a volume fraction of approximately 63 % for randomly packed and 74 % for hexagonal close-packed (HCP) sphere arrays. The hollow alumina spheres are commercially available sinter products. Five different sphere types with varying physical properties were investigated. The spheres were of two diameter sizes, 2.8 and 3.7 mm, with standard deviations of less than 7 % for each sphere type, while measured apparent sphere densities varied between 0.55 and 1.14 g/cm³. The average wall thicknesses were calculated from the apparent sphere density and the average sphere diameter, assuming the wall density as 3.87 g/cm³ for Al_2O_3 [7]. The wall thickness ranged from 93 to 175 μm. The CMMCs were fabricated using a gas pressure assisted infiltration casting technique, described elsewhere [6]. Infiltration process parameters were kept constant for all composite systems.

The dynamic modulus was derived from analysis of resonance frequencies of transversal vibrations in cylindrical samples, 15 mm in diameter and 80 mm in length. For compression tests with randomly packed spheres cylindrical samples, 20 mm in diameter and 30 mm in height, were prepared. For the HCP structures rectangular samples, 21 mm in height and 14 mm in width, were used. The aspect ratio was 1.5 in both cases. All specimens for mechanical testing were tested in the as-cast condition and machined on all sides to examine the properties of the materials structures without any surface skin effects. The average density of each sample was calculated by measuring weight and volume. In order to evaluate the mechanical properties of the magnesium matrix with no spheres, matrix alloys were cast using identical process conditions and machined to cylinders, 10 mm in diameter and 15 mm in height.

Uniaxial compression tests were carried out between two unlubricated hardened steel plates with an initial strain rate of $5.5 \cdot 10^{-3}$/s using an Instron 4505 testing machine. The compressive strength σ_c of the composite was defined according to ASTM Standard E 9-89a as the maximum stress at or before first fracture, i. e. the local maximum at the beginning of the collapse plateau.

3   Results

3.1 Microstructure

Optical examination of the composites showed good infiltration of the sphere arrays with magnesium, i.e. even the narrowest spaces between the hollow spheres were completely filled with metal (Fig. 1). The cell structure is closed-cellular and homogeneous, i. e. uniform in cell size and spatial distribution with spherical pores, as cell shape and size correspond directly to the morphology of the hollow spheres. It is one of the main advantages of this type of cellular material that the cell structure is not developed dynamically during fabrication, but predetermined by the packing of the hollow ceramic spheres. Therefore complete reproducibility of the cell structure is easily achieved.

Random packing of the spheres as illustrated in the X-ray picture of Fig. 1a implies an isotropic material behavior. In contrast, an anisotropic behavior is expected for an ordered sphere array like the HCP structure in Fig. 1b. In the latter case the close-packed planes, visible as broad stripes, are oriented in an angle of 45 ° to a vertical reference line representing the load axis in the deformation tests, i. e. the maximum shear stress acts on the close-packed planes and, consequently, the smallest possible material cross sectional area.
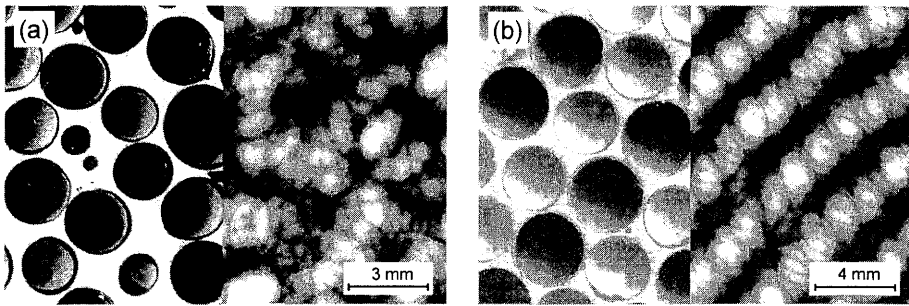
Fig. 1: Optical micrographs and X-ray pictures of a randomly packed cellular magnesium matrix composite (a) and a HCP structure (b) showing a closed spherical cell structure. The thin walls of the ceramic hollow spheres are recognizable as closed circles in the X-ray pictures. Close-packed planes in the HCP structure under an angel of 45 °.

3.2 Modulus and Strength

In order to give an overview of the mechanical properties of CMMCs and to compare their performance to currently available light metal foams, Fig. 2a shows modulus E plotted against density ρ and Fig. 2b shows compressive strength σ_c plotted against density ρ. In addition guidelines for the three performance indices for lightweight design are presented [8].
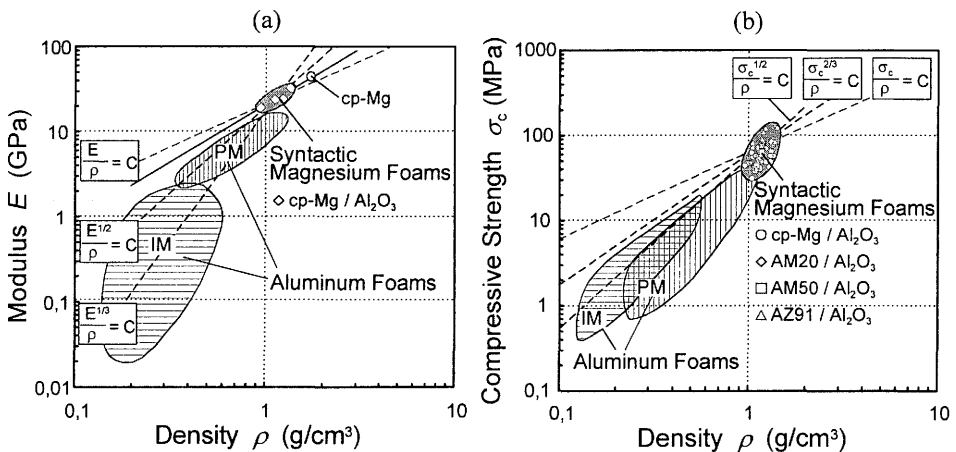

Fig. 2: (a) Modulus E plotted against density ρ and (b) compressive strength σ_c plotted against density ρ for syntactic magnesium foams (this paper) and currently available aluminum foams (data from Ref. [8]).

It appears that the specific stiffness and strength of the CMMCs is superior to all or most of the aluminum foams produced by powder metallurgical (PM) or ingot metallurgical (IM) routes in case of axial load or beam bending. In case of bending of panels the specific stiffness is comparable to conventional aluminum foams, while the specific strength is again superior to most of the other materials. As the plateau stress is almost equal to the compressive strength for optimized CMMCs and directly proportional to the energy absorption capacity per

unit volume [6], the ordinate in Fig. 2b could be converted to show the superior energy absorption capacity per unit mass of the syntactic magnesium foams.

The absolute value of density for the syntactic magnesium foams is higher and the range of densities is much smaller than for aluminum foams. The lowest density attainable is given by the spherical characteristic of the cells, i. e. there is a minimum volume fraction of 37 % for the matrix in randomly packed structures. Thus, the composite density is mainly controlled by the density of the hollow spheres and can be reasonably well predicted by the rule of mixtures. The sphere density was varied between 1.0 and 1.4 g/cm³ in the present case, corresponding to porosity levels ranging from 52 to 42 %. The compressive strength varies accordingly from 30 to 105 MPa and can be tailored to meet specific requirements. The respective contribution of the components will be discussed in detail below.

3.3 Influence of sphere morphology and matrix strength on compressive strength

The effect of hollow sphere morphology and the influence of the matrix compressive strength on the compressive strength of the composite is shown in Fig. 3 for random structures as well as for HCP structures. In the latter case testing was performed in such a way that the close-packed planes were under an angle of 45 ° to the load axis.
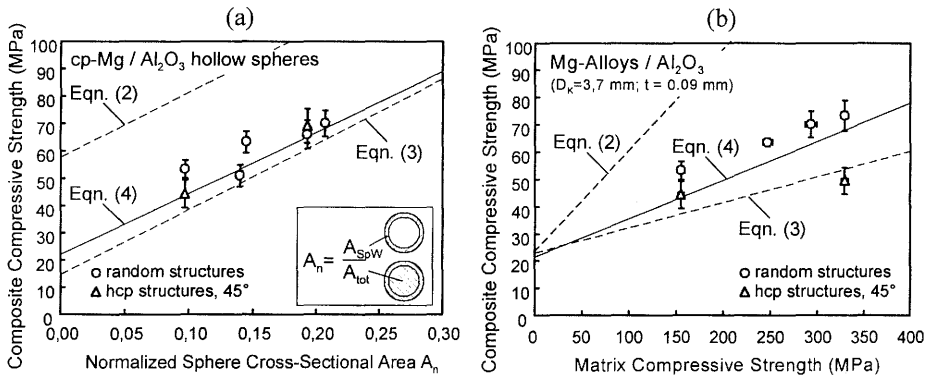

Fig. 3: Effect of hollow sphere morphology (a) and matrix compressive strength (b) on composite compressive strength.

Hollow sphere morphology in Fig. 3a is described by the normalized sphere cross sectional area, that is equal to the sphere wall cross section divided by the total sphere cross section. A value of $A_n=1$ corresponds to a completely filled ceramic sphere. This approach assumes that the load carrying area of the spheres is the most relevant parameter. A linear relationship is suggested by the data in Fig. 3a. Also a linear increase is observed for the compressive strength of the composite as a function of the compressive strength of the matrix alloy as shown in Fig. 3b.

4 Physical Model for the Prediction of Compressive Strength

In the following we will try to rationalize the compressive strength σ_c of cellular magnesium matrix composites, i. e. the stress maximum at the start of the collapse plateau. σ_c occurs at total strains ranging from 1.5 to 3.2 %. On a microstructural level it is characterized by the development of shear bands [5, 6] where plastic deformation and fracture of the matrix as well

as fracture of the hollow spheres has occurred. The shear bands develop in planes of maximum shear stress, that is planes inclined to the load axis by 45 °.

As the spheres and the matrix are strained equally, different stresses τ_{Sp} and τ_M will develop in both phases in the shear band. If A_{SpW}/A_0 and A_M/A_0 represent the area fractions of the two phases, where A_{SpW} and A_M are the load carrying cross section of the hollow spheres and the matrix respectively and A_0 is the total area of the cross section where failure occurs, mechanical equilibrium requires

$$\sigma = \frac{A_{SpW}}{A_0} \cdot \frac{1}{S} \cdot \tau_{SpW} + \frac{A_M}{A_0} \cdot \frac{1}{S} \cdot \tau_M = \frac{A_{SpW}}{A_0} \cdot \sigma_{Sp} + \frac{A_M}{A_0} \cdot \sigma_M \qquad (1)$$

where S, the Schmid factor, is equal to 0.5.

In order to calculate σ_c from Eqn. (1) we set σ_M equal to the matrix alloy compression strength $\sigma_{c,M}$ measured independently (Fig. 3). σ_{Sp} at the moment of fracture cannot be determined experimentally. For the sake of the argument, we assume that σ_{Sp} can be approximated by the tensile strength of alumina, $\sigma_{c,Sp} = 262$ MPa [7].

For the load carrying cross section in the composites an upper and a lower bound may be determined. Taking a sufficient volume of random spheres in a matrix, the stereological principle holds that the area fraction of the different phases is identical to the volume fraction. Thus the area fraction of the matrix in Eqn. (1) may be substituted by the volume fraction that has been determined experimentally as $A_M/A_0 = 0.37$. The corresponding value of 0.63 for the volume fraction of hollow spheres has to be multiplied with a factor taking the fraction of wall material into account. This factor, expressed as a function of outer sphere radius R and wall thickness t in Eqn. (2), is identical to the relative density of the hollow spheres. The composite compressive strength may then be written as follows:

$$\sigma_c^{upper\,bound} = \left[1 - \left(\frac{R-t}{R}\right)^3\right] \cdot 0.63 \cdot \sigma_{c,Sp} + 0.37 \cdot \sigma_{c,M} \qquad (2)$$

Comparing the calculated results according to Eqn. (2) with the experiments in Fig. 3 shows an overestimation of composite strength in all cases. Eqn. (2) can be considered as an upper bound, because it neglects the fact that the shear band can develop in areas with a particularly small material cross section.

A lower bound may be obtained by assuming that the composite fails along the plane of the smallest possible material cross section. In case of a close-packed plane the remaining matrix cross section in between close-packed spheres is only around 9.3 %, even though the volume fraction of the matrix is around 26 %. Assuming a close-packed plane is oriented parallel to the planes of maximum shear stress the lower bound for the composite compressive strength will be reached having the form:

$$\sigma_c^{lower\,bound} = \left[1 - \left(\frac{R-t}{R}\right)^2\right] \cdot 0.907 \cdot \sigma_{c,Sp} + 0.093 \cdot \sigma_{c,M} \qquad (3)$$

where the factor taking the fraction of wall material into account is equal to the normalized sphere cross sectional area A_n (see Fig. 3).

The calculated results according to Eqn. (3) in Fig. 3 are below the measured ones confirming Eqn. (3) to represent a lower bound. Fig. 3 also contains results for HCP structures. In this case, specimens were prepared where close-packed planes were produced deliberately.

The tests were then performed in such a way that the close-packed planes were oriented at an angle of 45 ° to the load axis (see Fig. 1). For this data Eqn. (3) does not represent a lower bound but the best approximation. As Fig. 3 shows, the experimental and calculated results do agree quite well with each other.

It is quite reasonable to assume that even for randomly packed spheres the shear band will sometimes be able to propagate along close-packed arrays over certain distances. This is why the experimental result lie between Eqn. (2) and Eqn. (3) in Fig. 3. In order to obtain a very rough estimate of the relevant matrix area fraction in a random array, we have plotted in Fig. 4 the matrix area fraction as a function of the matrix volume fraction for different packing arrangements.

As the volume fraction of the matrix in a random structure is known to be around 37 % the failure area fraction may than be estimated to around 14 % thus obtaining Eqn. (4) as an approximation for the compression strength of random structures:
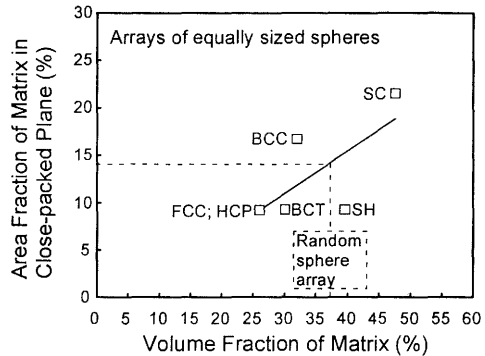

Fig. 4: Estimation of load carrying area fraction in random sphere arrays.

$$\sigma_c = \left[1 - \left(\frac{R-t}{R} \right)^2 \right] \cdot 0.86 \cdot \sigma_{c,Sp} + 0.14 \cdot \sigma_{c,M} \tag{4}$$

This equation (solid line in Fig. 3) is indeed in better agreement with the experimental results than the other approaches.

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