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Dynamic mechanical behavior of syntactic iron foams with glass microspheres

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ABSTRACT

In this work, the mechanical behavior of syntactic foams made of hollow glass microspheres mixed in an iron matrix was investigated. This type of material is interesting since, when compared to other types of metal foams, it offers greatly increased quasi-static compressive strength, though at lower maximum porosity and thus higher density. Moreover it maintains the advantages and useful properties of metal foams such as thermal and environmental resistance.

In particular, the strain-rate sensitivity response was studied. The experimental characterization was performed by means of compression tests at three strain-rate levels: at the highest strain-rate level a SHPB was used. Type and content of glass microspheres were also studied.

The experimental results showed that the compression behavior of syntactic foams, similarly to the other types of foams, is strongly affected by all the examined factors. For what concerns the strain-rate, it was found to increase material characteristics in almost all cases. The influence of the matrix behavior on the composite was identified as the determining parameter in this respect.

In order to evaluate the results obtained with the described tests campaign, the experimental data were further elaborated by means of an empirical analytical strain-rate sensitive model. The dependency of the material response on model parameters was widely discussed.

1. Introduction

In recent years, the attention of several researchers was focused on the development and characterization of a particular class of foam structures, the syntactic foam, in which hollow spheres are dispersed in a continuum matrix.

From a mechanical point of view, the behavior of syntactic foams is quite similar to the behavior of a metal matrix composite combined with features of conventional foams. As a matter of fact, there are two distinct phases: a matrix in which there is a dispersion of particles, hollow in particular. In general, the resulting behavior of a composite material depends on both matrix and dispersed second phase mechanical properties but also on their interaction. In the preparation of the syntactic foam, different types of particles can be used, e.g. foam glass granules, metal spheres, ceramic spheres [1,2] and glass bubbles [3–7]. The matrix can be polymeric [3–7] or metallic [1,2,8–10].

When compared to correspondent dense materials, this class of materials exhibits lower density combined with high strength and energy-absorbing capabilities. This combination makes this class of materials suitable for several applications, like structural sandwich cores, impact-absorbing applications, crash safety and packaging. The mechanical response is influenced by several parameters, such as density, type, structure and dimensions of the particles, type of matrix and loading conditions [11,12]. When contrasted to metal foams based on the powder compact melting or the APM process [13], the iron matrix syntactic foams combine lower maximum porosity and higher density with greatly increased quasi-static compressive strength while showing the typical deformation characteristics of foams. As a matter of fact, the achievable level of porosity stays below the respective value of other types of foams. Thus, the lowest density which can be obtained is higher, or similarly, from the point of view of porosity, the maximum porosity is lower with respect to other foams.

In several works the influence of the reinforcement content on the material behavior was investigated. Tao and Zhao [2] analyzed the quasi-static compressive behavior of an aluminum matrix syntactic foam varying the volume percentage of the matrix content. This was reached by toughening the matrix with aluminum particles improving the ductility and the compressive strength of the foam. The quasi-static behavior in compression was studied also by Swetha and Kumar [3] depending on the filler properties. Viot et al. [7] showed that varying the microsphere volume fraction (and consequently the density) produce the effect of changing the damage mechanism. In particular, for low particle content the main damage mechanism is the fracture of the microspheres. On the other

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hand, for high particle content the material damage is due to the matrix failure. The latter aspect can be explained by the fact that, due to the high particles content, the amount of bonds in the matrix is limited. Similar studies were performed by Gupta et al. [6] and Shunmugasamy et al. [5], in which the behavior of the syntactic foam was investigated for different strain-rates, polymeric matrices, micro-balloon types, and percentages of glass content. Dou et al. [9] analyzed the cenospheres-pure aluminum syntactic foam focusing the attention on the influence of the particle dimension in different strain-rate loading conditions, comparing the results with the pure matrix samples. In [9], the authors also provided the calculation of the strain-rate sensitivity parameter and developed a three parameters data-fitting analytical model to predict the dynamic compressive strength of the foam. In [14] different aspects, such as morphology, topology, sphere wall thickness and strain-rate sensitivity were analyzed. The objective was the investigation of the macroscopic behavior of metallic hollow sphere structures by means of computational simulations.

In this work the attention was focused on the mechanical characterization of the behavior of a metallic syntactic foam in a wide range of strain-rates. Since a metallic syntactic foam shows properties both of metallic foam and metal matrix composite, its behavior at high strain-rate is shown to be quite complex. The quasi-static mechanical behavior of different types of syntactic foams under uniaxial compressive loading condition was widely investigated in recent years, see e.g. [2,3,6]. Several studies were also performed in order to understand the syntactic foam behavior at high strain-rates, see e.g. [1,4,5,7,9]. In general, it was found that the compressive strength of the syntactic foam is controlled to a large degree by the strength of the matrix. This implies also that the strain-rate sensitivity of the foam is close to the matrix one.

The syntactic foam analyzed by the authors was made of a pure iron matrix with a dispersion of hollow glass microspheres. It was obtained by means of metal powder injection molding (MIM) [15]. The parameters taken into account in the evaluation of the material behavior were the microsphere content (5, 10 and 13% in weight), the type of microspheres (S60HS and iM30K) and the strain-rate. The experimental tests performed were compression tests from quasi-static up to high dynamic loading conditions, covering 6 orders of magnitude in strain-rate. The choice of this type of loading (i.e. compressive), even though apparently too simplistic, still covers most of the envisaged energy absorption applications.

Starting from the analysis of the experimental results, the authors propose the numerical fit of the data with an empirical strain-rate sensitive model [16]. The authors widely discussed the influence of each parameter of the model, focusing the attention on their trends in function of both type and percentage of glass.

2. Iron syntactic foams

Several production methods for syntactic foams exist, such as melt stirring, melt infiltration or powder metallurgy processes [17]. In the current literature, production techniques based on the infiltration of solid structures or loose bulks of the hollow elements by metal melts represent the dominant approach. Since metal melts do not usually wet the hollow particles, pressure-assisted infiltration techniques like gas-pressure infiltration or squeeze-casting are frequently used [18]. For alloys with high melting temperatures, like iron or steel, liquid infiltration of microsphere structures is extremely difficult. Only few techniques like gas-pressure infiltration are available and the combined impact of high pressure and temperature during the filling stage can lead to the destruction of the micro bubbles which have wall-thicknesses of few microns.

Alternative approaches to the melt infiltration can be based on powder metallurgical techniques like pressing or metal powder injection molding (MIM [15]). In the latter process, which is closely related to polymer injection molding, the forming step is carried out at moderate temperature (110–140 °C), whereas the subsequent pressureless sintering process is done at temperatures of around 2/3 to 4/5 of the melting point of the respective material. Obviously, this still exceeds the softening point of a lot of microsphere types. However, it could be shown that the interaction of metal powder and microspheres leads largely to a preservation of the shape and a limited reduction in the size of the hollow spheres – even though they have only weak internal residual strength at the applied sintering temperatures. The feasibility of this approach could be shown for several high-melting alloys like pure Fe, FeCu3 or FeNi36.

3. Experimental procedure for material production

Following the above-mentioned approach, syntactic Fe99.7 foams containing different weight percentages of glass microspheres were synthesized: for sample production, a feedstock was prepared which contained approximately 50 vol.% of pure Fe (Dr. Fritsch GmbH, purity 99.7, d_{50} = 1.4 μm), a binding agent as well as different glass microspheres weight fractions (5, 10 and 13 wt%) and two different glass microsphere types (S60HS e iM30K). The hollow elements are commercial hollow glass microspheres, produced by 3M and made of soda-lime borosilicate glass. Both of them are specially formulated for a high strength-to-weight ratio. This guarantees greater survivability during injection molding. The main properties of these glass microspheres are reported and compared in Table 1. The two types of glass microspheres have the same density (0.6 kg/dm^3). Since the average diameter of the microspheres is higher in the case of the S60HS glass, their estimated wall thickness exceeds that of the iM30K variant. Nevertheless, the maximum allowable injection pressure to obtain a percentage of failed microspheres between 80% and 90% is higher for the latter.

The values given for the weight percentage of glass microspheres refer to the combined mass of metal and glass in the final composite material (sintered part). In addition to these components, the metal injection molding feedstock contained a polymer–wax binder which was matched in volume to the Fe content. Mixing and feedstock homogenization took place using a Brabender-CE equipment. The final feedstock was injected into a tensile test specimen mould at 110 °C (mould temperature 50 °C) and 4 bar using a HEK injection molding machine. The binder was removed via a combined chemical (48 h at 25 °C in hexane) and thermal process (holding at 500 °C for 60 min after heating-up at 0.1 K/min) with subsequent sintering for 90 min at 900 °C in H_2 atmosphere following a temperature ramp-up at 5 K/min. For reference samples (pure Fe samples), the same feedstock was used without the addition of microspheres.

Different mixtures were prepared and the properties of the sintered materials are shown in Table 2. Using 0.6 kg/dm^3 as density of the glass microspheres and 7.87 kg/dm^3 for that of pure iron, the theoretical density of perfect syntactic foams was calculated. The composition affects the resulting material density that varies from the pure iron density to less than half of its value at 13 wt% microspheres content. In Fig. 1, the results of the light microscopy of the metallographic sections of the syntactic foams analyzed in this work are shown. It can be seen that the foam quality is very good for Fe with S60HS glass bubbles, whereas in the case of iM30K more destroyed glass bubbles were found. This might be explained by increased chemical interactions at the larger interface between matrix and the glass bubbles of the iM30K type.

The samples were provided in dog-bone shaped specimen (Fig. 2a). The rounded shape, with approximately 4 mm diameter, is particularly fit for manufacturing purposes. Preliminary tests performed in tension showed that the introduction of glass