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Optimization of the process parameters for the manufacturing of open-cells iron foams with high energy absorption

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Abstract

In this work the main results of the experimental research aimed to manufacture iron foams are reported. Iron powders (base metal) have been mixed with urea (filler agent) in different relative amounts (60% Fe- 40% urea, 50-50, 40-60 and 30-70) and then compressed in a cylindrical die in order to obtain a compact precursor. After compaction, the filler agent has been removed from each precursor in boiling water. The successive manufacturing step has been sintering and for this operation the optimum temperature has been found at 950 °C. Finally such foams have been subjected to compressive tests. Different amounts of Fe and urea match with different density and mechanical behavior in compressive tests. Energy absorbed during deformation has been calculated from the stress-strain compressive curve. Plateau stress, total strain and absorbed energy during deformation have been found strictly dependent from the iron/urea ratios.

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Keywords: Cellular metals, Manufacturing, Iron foams, Mechanical Characterization.

1. Introduction

Metal foams are a relatively new class of materials (Banhart 2001, Costanza et al. 2003) and different production processes for their manufacturing have been developed during the last years. The most common one starts from powders of the base metal, mixed together with a foaming agent (TiH_2) and a stabilizing agent (SiC). After compaction the precursor is inserted in a oven set at temperature higher than the melting point so that foaming can occur in few minutes. The powder mix composition is extremely important for the Al foam morphology (Costanza et al. 2008) but the main limit is due to the melting point of the base metal that in such production process must be in good agreement with the decomposition temperature of the blowing agent. An alternative process, developed for

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high melting temperature alloys, in which the base metal and the filler agent are mixed and compacted together (Zhao 2001) has been defined. After removal of the filler agent, in the successive manufacturing steps, some voids airbubble-like lay equally distributed in the volume (Costanza et al. 2011, Deqing et al. 2003, Ip et al. 1999). Dealing with applications, metal foams are usually employed for light structures (Costanza et al. 2004, Costanza et al. 2008), according to the weight reduction up to 80% of the base metal, mechanical strength and stiffness, high energy absorption structures in compressive tests (Banhart et al 1998, Costanza et al. 2012, Olurin et al. 2000; Yi et al. 2001), crushing (Seitzberger et al. 1997) and finally thermal, acoustic and vibrational insulation. Fe (Park et al. 2001), Al (Costanza et al. 2005, Costanza et al. 2015) and Pb (Irretier et al. 2005, Costanza et al. 2013) and their alloys are the most commonly foamed metals. Recently also metal tubes filled with foams have been characterized by means of compressive tests (Bonaccorsi et al 2010, Costanza et al 2014, Costanza et al 2015).

2. Materials and experimental

In this work open-cell foams production has been performed by Sintering – Dissolution Process (Zhao et al. 2001, Costanza et al. 2011). SDP method consists in the following four steps processes: mixing, compacting, dissolution and sintering. The SDP technique has been adopted and suitable modified according to the Fe main characteristics. The base materials are Iron (>99%) powders (70 μm average diameter), Urea (2 mm average diameter) as filler agent and acetone as a binder. The choice was driven not only by the easy dissolution process (water at 100 °C is enough) but also by the relative low cost. Before compaction, Fe powders, filler and the binder have been mixed (five minutes is enough) to obtain a uniform distribution of both components. After mixing acetone binder was evaporate in the air. In order to obtain precursors, powder mixtures were compacted in a mould, by means of hydraulic press, choosing the optimum load for crushing superficial oxide on powders, applying up to 680 MPa. Before sintering the obtained precursor has been successively washed in hot water (100 °C) in order to remove the filler (urea). The successive step of this process has been sintering. Many experiments have been performed and an optimal temperature and time have been identified (950 °C for 30 minutes) for sintering process in order to obtain a satisfying compressive behavior of manufactured foams. Sintering times shorter than 30 min were not sufficient to ensure adequate bonding and sintering time longer than 30 min may lead significant oxidation of Fe matrix. Different compositions of Fe and urea % were considered. In this paper the main results about 60-30 % Fe and 40-70 % urea will be showed. Out of these ranges it has not been possible to manufacture satisfying foams. For each composition three samples have been produced to confirm the reproducibility of the results. In specimens having the same composition a low scattering of data has been observed.

An example of iron foam performed with SDP method with 60% of iron and 40% of urea is shown in Figure 1.

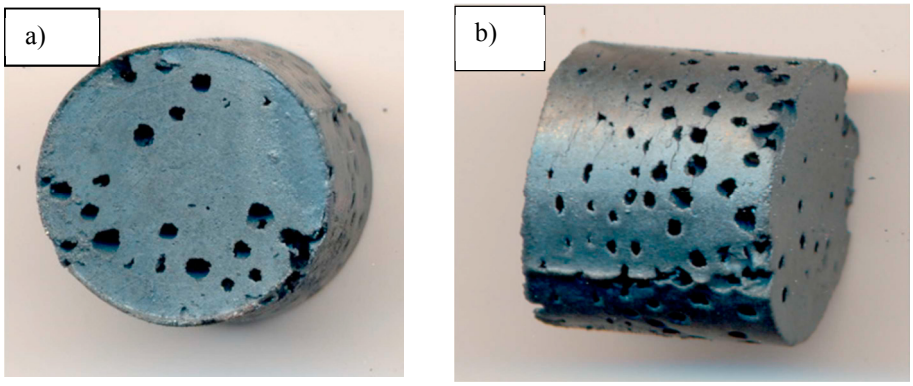

Fig. 1. (a) iron foam 60% Fe-40% urea, front view; (b) iron foam 60% Fe-40% urea, lateral view.

3. Results and discussion

Compression tests were carried out on cylindrical samples (ϕ = 15 mm, h = 12 mm). The parallelism between the two platens was adjusted through the examination of the contact surface between them before the compression test.

For each sample, the compression test was performed with MTS Insight 50 kN machine and a crosshead speed of 2 mm/min has been selected with a data acquisition frequency of 5 Hz. The main results of compression tests are reported in Figure 2 for foam manufactured with different composition: 60% Fe-40% urea, 50% Fe-50% urea, 40% Fe -60% urea, 30% Fe -70% urea. The compression curves show a strong dependence of the behaviour from the Fe amount (and consequently from the density of the foam), in particular the elasto-plastic limit, the value of the plateau stress and the level of strain on which the final densification occurs. The lower the Fe amount in the foam the lower the foam density and consequently the lower (in term of stress and strain) the elasto-plastic limit while longer strain under constant deformation load and lower plateau-stress appear.

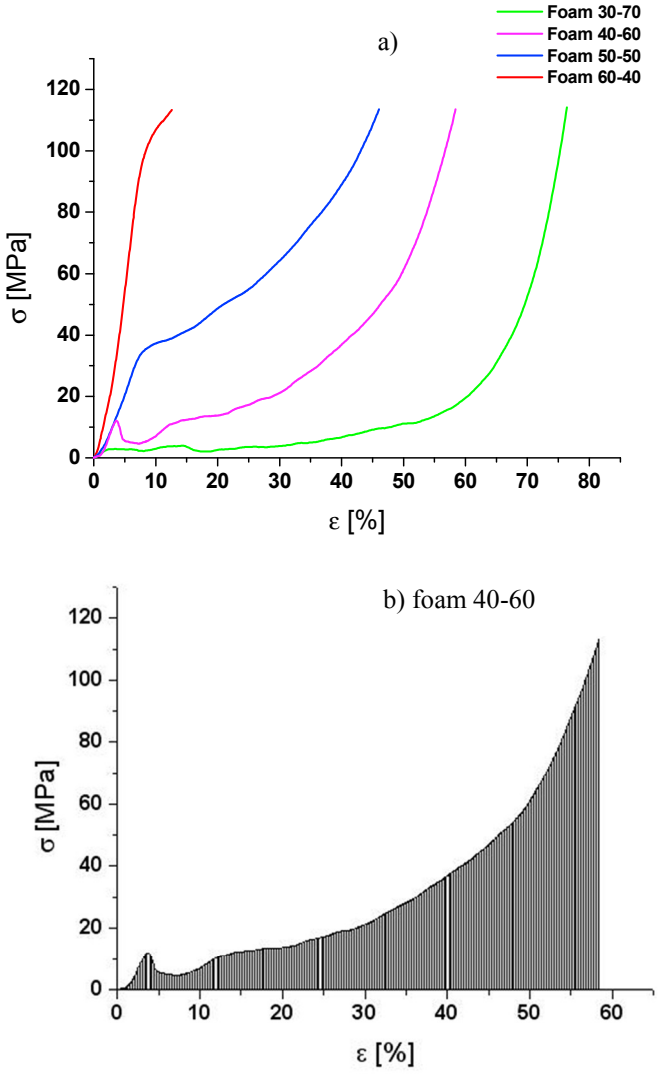

Fig. 2 (a) Stress-strain curve of Iron foam with different composition: 60% Fe-40% urea, 50% Fe-50% urea, 40% Fe-60% urea, 30% Fe-70% urea. (b) The absorption energy by unit volume, corresponding to the area under the stress-strain curve.

The trend of the curves is strictly dependent on the relative amount Fe-urea: in terms of mechanical behaviour (σ-ε curve, plateau stress, total strain %) a good compromise between composition and performance of the compressive strength is represented by 40% Fe-60% urea foam. Despite the small load fall, probably due to the inhomogeneous distribution of pores, and then the initial failure of some wall porosity, the foam shows excellent strength properties,

with a good trend of the curve: a 50% deformation, for example, corresponds to a high stress value, equal to 60 MPa. In the figure below (fig.3) the aspects of foams with different composition are shown. It's evident that the amount of porosity is most relevant in the foam with larger amount of urea (70%).

The energy absorption capacity is defined as the energy necessary to deform a sample up to a specific strain level. The absorption energy by unit volume of a sample can be evaluated by integrating the area under the stress-strain curve as showed in figure 2 b) for the 40-60 foam. Results of density and energy absorption in compressive tests are reported in Fig. 4 a) and b) for the selected composition Fe-Urea.

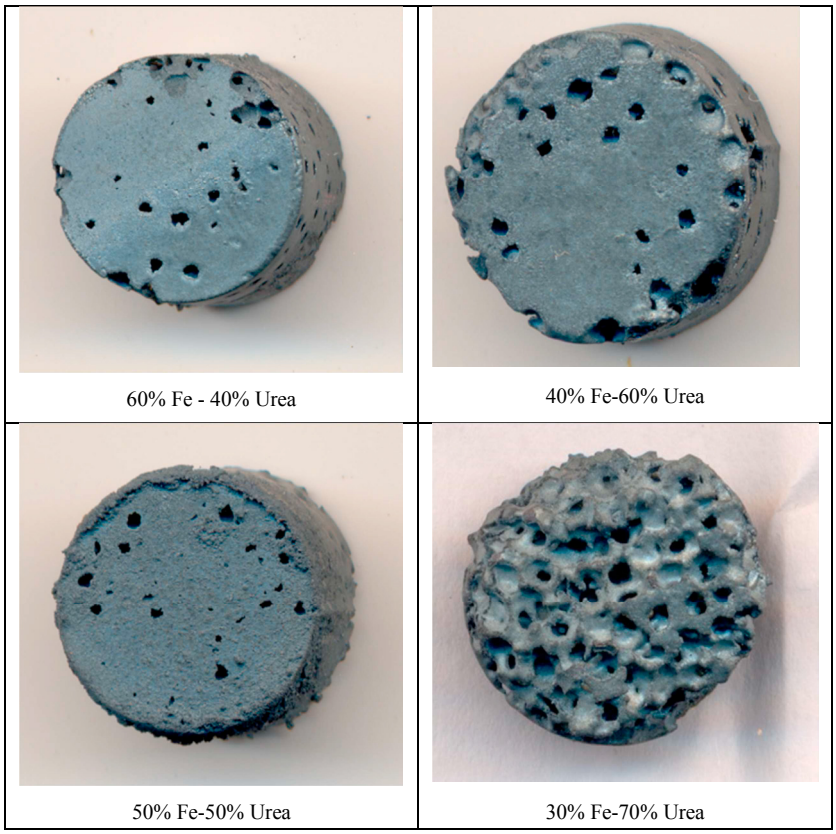

Fig. 3 Images of foam with different composition: 60% Fe-40% urea, 50% Fe-50% urea, 40% Fe-60% urea, 30% Fe-70% urea

The smaller Fe amount the lower weight and density of the manufactured foams. Weight and density are the most important parameters for the evaluation of the foam quality. As reported in Fig. 4 a) the 40-60 foam shows a density of 2,77 g/cm^3, corresponding to a 65% reduction of weight in comparison with massive iron. It is an extremely significant result, taking into account also the good mechanical properties shown in the compression test (Fig. 2 a).

In general, the higher the urea amount, the lower the density of the foam. The best foam considering only the porosity is represented by the 30-70 one. Voids appear homogeneous and equally distributed and in terms of mechanical characteristics it is corresponding with the lowest plateau stress and highest deformation strain. By the way this solution doesn't represent the best result in terms of energy/density ratio, as shown in Fig. 4 b).

As reported in Fig. 5 a linear relationship between the deformation strain and the density has been found: the higher the density the lower the deformation strain and vice versa. For what concerns the specific absorbed energy (energy / density) the highest value has been achieved in the 50-50 foam in combination with the intermediate

measured values of both stress and strain. For extremal values (high stress and low strain, 60-40 foam; high strain and low stress, 30-70 foam) the specific energy is always lower.

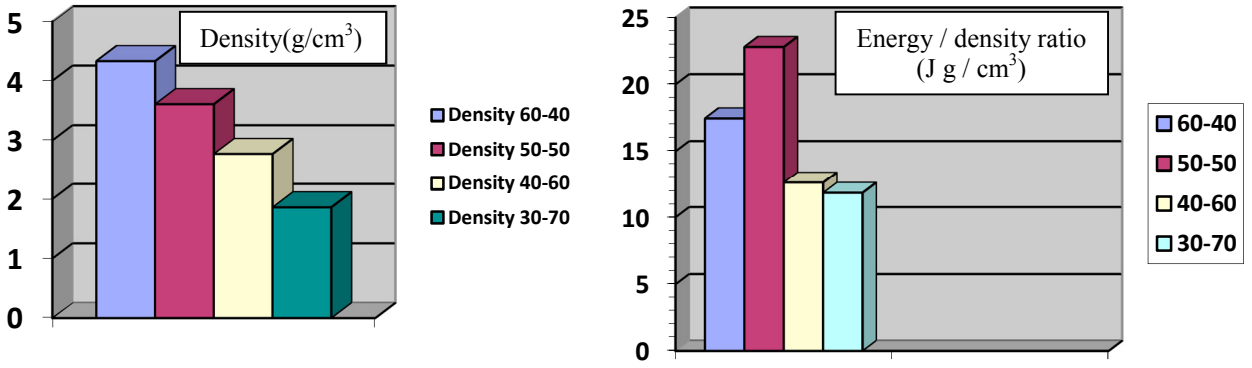

Fig. 4 (a) ρ density (g/cm^3) of foam with different composition: 60% iron-40% urea, 50% iron-50% urea, 40% iron-60% urea, 30% iron-70% urea. (b) The energy/density ratio (J g / cm^3) for the 4 considered foams on the left.

Tab. 1 Physical properties comparison

Physical properties				
	60 Fe – 40 Urea	50 Fe – 50 Urea	40 Fe – 60 Urea	30 Fe – 70 Urea
Weight (g)	9,19	7,34	5,38	3,3
Diameter (mm)	15	15	15	15
Surface (mm^2)	176,6	176,6	176,6	176,6
Height (mm)	12	11,5	11	10
Volume (mm^3)	2.120	2.031	1.493	1.766
Density (g/cm^3)	4,3 (-45%)	3,6 (-55%)	2,8 (-65%)	1,8 (-76%)

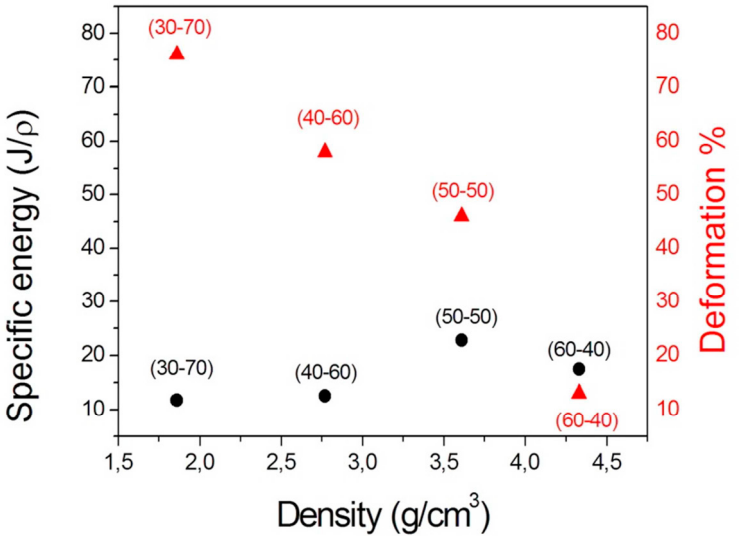

Fig. 5 Energy, density of foam with different composition: 60% Fe-40% urea, 50% Fe-50% urea, 40% Fe-60% urea, 30% Fe-70% urea.

4. Conclusion

The accurate evaluation of the mixture composition is fundamental for the prediction of foams mechanical properties which are strongly dependent on the Fe and urea amount and consequently on the foam density. The compression tests have shown the optimal mechanical strength of the manufactured Fe foams and their energy absorption ability. The porosity amount is strictly connected to the greater presence of urea and, just looking to the density and the deformation strain, the 30-70 foam represents the best composition. But in the evaluation of the overall performance of the foam it is necessary to take into account also other properties, that are: energy absorption, deformation strain and plateau stress. From this point of view other solutions offer a good mix of physical and mechanical properties; between the analyzed ones in this work also the 40-60 and the 50-50 foam must be considered.

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