Al-Based Metal Foams

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Metal Foams (MF) are tridimensional metal matrices which can be defined as mixtures of metal and gas (generally gas volume fraction is higher than 70% and relative density is lower than 0.3). *MF can have open or closed cells, which means that porosity can be interconnected or not, respectively.* Metal foams are extremely interesting due to their low density, high specific stiffness, and impact energy/vibration absorption ability. The use of metal foams as permanent cores in casting can be an opportunity to improve the properties of cast components and to simplify the technological processes (e.g., no need for core removal/treatment/recycling).

metal foam,casting,permanent cores,aluminum

1. Introduction

Porous materials for structural applications are present in nature (e.g., wood and bone) and can be the inspiration for the development of innovative synthetic materials, such as metal foams, which can be of interest for their unique properties such as low density, high specific stiffness, energy and sound absorption, thermal insulation, fire resistance, and recyclability [1]. Due to their superior specific mechanical properties, mainly closed-cell Al-based foams are used for structural applications. These materials are of particular interest in the automotive and aerospace industries for lightweight construction, energy absorption, damping, and insulation [2]. However, the use of Al-based foams has not spread so much due to difficulties in production process control (which often lead to inhomogeneous structures) and high costs [3]. Moreover, despite their very promising properties, often Al-based foams by themselves are not the solution for practical applications, while more interesting performances can be reached by the development of sandwich structures or hollow structures with a foam core [2][3]. Al-based foams sandwiches have been successfully obtained, without the use of polymeric adhesives, for example, by means of brazing [4][5], rolling technologis [6], or in situ foam filling of tubes [7][8]; these last examples have been proposed for automotive applications [2] as crash absorber or as engine mount (foam core with cast shell). However, most of these topics are still poorly explored and only occasionally developed at the industrial level. One of the latest examples that has been found in the literature was the use of metallic foams as a permanent core in cast components [9], resulting in an interesting and promising application for the realization of functional cores, like in the case of some natural components, which can impart specific properties to the final object (e.g., stiffness or energy absorption) and, at the same time, can eliminate the need of removal and recovery of the traditional sand cores. Despite the promising prospect, this topic is still poorly explored and, in any case, away from its technological application and engineering.

2. Closed Cells Al-Based Foams

Metallic Foams (MF) can be defined as mixtures of metal and gas in which the volume gas percentage is significantly higher than the metal one; in particular, these cellular materials are defined as tridimensional metal matrices in which the gas volume fraction is higher than 70% and relative density is lower than 0.3 as described by [10].

The main distinction of the MF is between closed and open cells. The closed-cell metal foams, in the opposite way from open-cell ones, are characterized by not interconnected pores (cell), which are separated by thin metallic walls. Their mechanical properties are superior to the ones of open-cell MFs and consequently, these materials are preferred for structural applications (e.g., in the automotive and aerospace fields). Moreover, the presence of closed porosities can obstacle the infiltration of molten metal in the foam core during casting.

Various processing technologies are nowadays available to produce Al-based metal foams with different characteristics, as comprehensively summarized by [2][10][11][12][13].

Technological strategies for the production of metallic foams can be classified considering the state of the metal during foaming (liquid, solution/emulsion, or solid), the forming process (casting, foaming, deposition, or sintering), or the pore-forming method (introduction of hollow/removable patterns, direct gas injection or use of precursors) as suggested by [10]. Alternatively, as proposed by [11], foaming processes can be classified considering the way of foaming such as, direct and continuous foaming of molten metal (by means of gas injection into the melt) or indirect foaming, which is a batch process based on the use of a precursor (the precursor release gas upon melting).

The majority of the processes for foams production can be defined as self-formation routes because gas bubbles are generated in the metal and lead to foam formation. These technologies produce foams with stochastic pores distribution that cannot be defined during product design and which can lead to inhomogeneous structures with mechanical properties lower than the theoretical ones [3].

More homogeneous pore size and distribution can be obtained through production methods that use templates instead of foaming agents. Metal foams can be obtained in this case by casting liquid metal around inorganic/organic low-density spacers, such as hollow spheres, salt beads, or woven wire meshes [13]. These objects can remain in the final foam (syntactic foam) or can be removed by means of chemical or thermal treatments [12]. The lost precursor method (analogous to investment casting), the use of polymeric/ceramic templates as negative molds, or the sponge replication method can be also cited among the template-based techniques for the preparation of metal foams [13]. However, most of these strategies produce open-cell foams and are often developer only at a laboratory scale without having seen extensive practical production and/or commercial applications.

The most common industrial routes employed for the production of closed-cell Al-based-foams are briefly summarized in the following.

Production of closed-cell Al-based foams through direct gas injection in the molten metal is described in [2][14][15] and commercialized by Cymat/Alcan, to cite an example [16]. The involved material is generally an aluminum alloy added with 10–30% of ceramic particles (SiC or Al_2O_3, MgO) with average dimension 5–20 µm, and a gas (air, nitrogen, or argon) injected into the melt through a rotating impeller or a vibrating nozzle to develop a homogeneous dispersion of gas bubbles. The process parameters (gas flow, rotor type, and rotation speed) allow the tailoring of gas bubbles dimensions, while the ceramic particles stabilize cell walls by increasing liquid viscosity and avoiding bubble collapse. By continuously pulling off the liquid–foam from the surface and cooling down it thought movable plates, foam panels with density in the 0.05–0.55 g/cm^3 range and with cell dimensions between 2.5 and 30 mm can be obtained by this route. The as-prepared panels present a dense outer skin, which is, however, not completely homogeneous. They can be directly used or cut in defined shapes for applications. As an example, the continuous process developed by Cymat produces 900 kg/h of Al-foam panels (1.5 m width 25–150 mm thick) at reasonable costs. In this kind of process, the gas injection step has been investigated and optimized (considering gentle gas generation), in order to obtain more uniform bubbles and consequently more uniform pores in the final foam (Metcomb) [17].

Production of closed-cell Al-based foams through in situ gas generation is described in [2][14][15] and commercialized as Alporas foams (Shinko–Wire method), to cite an example [18]. According to these routes, gas bubbles are generated by the decomposition of a solid precursor. The Shinko–Wire process foresees the optimization of the viscosity of the molten metal through the addition of about 1.5% wt. calcium metal at 680 °C; its affinity for oxygen makes it work like a deoxidizer, thus inducing the formation of compounds, e.g., CaO and $CaAl_2O_4$, which increase the melt viscosity. The dense molten metal is then transferred into a die where the foaming agent (TiH_2 as a solid precursor, typically 1.6 %wt.) is added and vigorously stirred to induce hydrogen development and, therefore, bubble formation. Large foam blocks (450 mm × 2050 mm × 650 mm) with a density in the range 0.18–0.24 g/cm^3 and with average cell dimensions of about 4.5 mm are produced by this process [14]. Alporas foams find applications as sound absorbers due to their optimal sound and shock absorption properties [18]. The FORMGRIP (Foaming of Reinforced Metals by Gas Release in Precursor) process belongs to the same category [19]. In this case, TiH_2 is mixed with molten metal, containing 10–15% vol. SiC particles to increase the viscosity of the melt, and gradually cooled to room temperature. To avoid TiH_2 premature decomposition, its production must follow a rapid solidification and the particle powders should be oxidized [2]. This composite precursor is then transferred in a graphite mold, heated to obtain melting, with TiH_2 decomposition and the consequent foaming until the mold is filled. The foam is then cooled and extracted from the die. The mean diameter of cells developed by this route is inversely proportional to the density of the melt. The main advantages are that the melt is not transferred during the foaming process (compared to the Shinko–Wire method) and that the shape of the final foam block can be varied and defined before foaming. On the other hand, the main disadvantage is that it is a multi-step process with higher costs than Cymat and Alporas ones [14].

Production of closed-cell Al-based foams through powder compaction method is described in [1][2][15][20][21] and commercialized as Alulight [22], IFAM-FOAMINAL [23], or Havel Metal Foam [24]. The process foresees at first by mixing the metallic powders with foaming agent ones and then by compacting the powders (e.g., uniaxial or isostatic pressing, rod extrusion, or rolling) in order to obtain a compact object with negligible or reduced porosity. Finally, the "green compact" is heated to melt the metallic matrix and decompose the foaming agent. Roll cladding of the foamable precursor with Al dense sheets allows the production of Al–Al foam sandwich panels [2]. Commercial panels (625 mm side and 8–25 mm thick) are produced by this route [1][20][21]. It has been reported that the preparation of thicker panels by means of this method can lead to a non-homogeneous pore distribution (denser structures at the center of the large ingot was obtained), due to the incomplete hydrogen development at the core, which does not reach the requested temperature for foaming [25]. This research highlights a direct correlation between the sampling zone, the obtained porosity, and the mechanical properties of the samples.

Among the above-described processes, only the last one produces foams with a continuous and homogeneous external skin with a surface thickness comparable to the thickness of the pore walls (about 200 µm) [26].

Also, Cymat foams present a surface layer, but it is not continuous and homogeneous. In addition, a continuous external skin (with a thickness of about 400 µm) was produced with Alporas foams using the Incremental Stir Forming process [27].

Of course, depending on the final application, different geometries of aluminum foams may be required. Large panels are of interest for impact energy absorption (e.g., car components), sound absorption (e.g., machine casings, soundproof walls), packaging, furniture, and blast protection, to cite some examples [3]. On the other hand, sandwich panels or shaped parts are required in order to obtain stiff and super lightweight objects, to replace sand cores in casting, and to obtain floating structures [3]. Cymat technology is the most economical for the production of large panels while powder routes (FOAMINAL and Alulight) are necessary to obtain panels for shaped parts [3]. Finally, the Functionally Graded (FG) aluminum foams are characterized by different porosity along the component; these foams are produced starting from gas-rich die casting metal by means of friction stir processes [28]. The possibility to prepare Al-based foam to Al sheets sandwiches from different kinds of foams by means of the joining process has also been explored in the scientific literature [4][5][29][30].

It was reported [31] that the main parameters of foams that affect their final properties are: the properties of the material that constitute the foam, the relative density (foam density/bulk material density), foam type (close/open cells), irregularities/defects, dimension, shape, distribution of cells, and their connection. Among them, the highest influence is determined by the relative density, which, for commercial closed-cell Al-based foams, is generally comprised between 0.02 and 0.2 [9].

Considering the mechanical properties, foams characterization is mainly performed via compression due to the difficulties in the set-up of the tensile test (e.g., problems related to samples clamping without damage and artifacts introduction). Three main regions of the stress–strain curve, obtained from compression tests, can be defined as follows: the first linear tract, a plateau with an around constant load for a large amount of deformation, followed by a final rapid increase in the required stress due to the collapse and densification of the cells. During the compression, the initial tract is not perfectly straight, because of the premature yielding of some cell walls and with a slope that depends on the relative foam density in respect to the bulk material. The presence of a plateau is of great interest in energy-absorption applications; the longer is the plateau, the higher the adsorbed energy [9][15][31].

A strain-rate dependent strengthening has been observed in closed-cell aluminum-based foams (Alporas) and it has been attributed to the flow of the gas (entrapped in the cells) through the cell structure during the test [32]. Furthermore, a dependence of this phenomenon from foam density and cell shape, size distribution, and walls uniformity/section was also observed.

As far as thermal properties are concerned, the melting point, specific heat, and thermal expansion coefficient of Al foams are substantially close to the ones of dense Al. It has been reported that the real melting point of Al-based foams can be slightly higher than that of the dense Al-alloy (up to 780 °C) due to the presence of a surface oxide layer on the cell walls [1], which can prevent the collapse of a cell wall at a temperature above the melting point. On the other hand, the thermal conductivity is lower when compared to the dense metal because the amount of dense metal is lower and the gas, trapped in the foam pores, markedly reduces the heat conduction [1][9].

Finally, concerning acoustic properties, metal foams can be particularly advantageous at low and intermediate frequencies fields (up to the critical frequency, e.g., at about 300 Hz for an Al-Si closed-cell aluminum foam with density 0.51 g/cm^3 and thickness 30 mm [33], dominated by stiffness and resonant frequency, respectively), while lower benefits can be obtained in case of higher frequencies (controlled by the mass) [31]. In this case, since the best acoustic absorption performances can be obtained for high permeability materials, open-cell foams perform better [31].

Furthermore, in the case of closed-cell aluminum foams, the absence of an external continuous skin showed a better sound absorption behavior when compared to their counterpart with dense skin; some surface mechanical processing (such as drilling, rolling, or compression) have been successfully used to improve sound absorption ability of closed cells aluminum foams with a continuous skin, by means of the creation of discontinuities in the surface skin or the pores walls [31][34][35].

3. Characterization of Metal Foams and Cast Objects Containing Metal Foams

Several techniques, both destructive and non-destructive, are currently used for the characterization of metal foams [12].

Optical microscopy is widely used for the characterization of metal foams after metallographic preparation of the sample (cutting of a representative sample, resin mounting, mirror polishing, and eventual metallographic etching) [12]. This technique allows for the investigation of pore size and distribution, cell walls, and skin thickness and uniformity, as well as the metal microstructure. The chemical composition of the foam and the microstructure can be analyzed also by means of Scanning Electron Microscopy equipped with Energy Dispersive Spectroscopy (SEM-EDS), after proper sample preparation (analogous to optical microscopy one, with the optional addition of surface metallization in order to make conductive resin mounted samples). The foam chemical analysis alone can be detected with high precision after foam melting in inert gas or vacuum and, after solidification, by adopting Optical Emission Spectroscopy (OES) or Inductively Coupled Plasma (ICP) mass spectrometry instruments.

Mechanical tests (mainly compression and bending test, but also tension, shear, or torsion ones have been cited) in quasi-static (most widely reported) or dynamic and even cyclic conditions can be applied after properly foam samples preparation in order to investigate their properties and suitability for structural applications [12][32][36]. A high variability of the results can be associated with foam inhomogeneity and can require a higher number of specimens, when compared to dense metal, in order to have representative results [12]. Moreover, sample preparation has to take into account the pore dimension and its distribution in order to avoid edge effects; for example, it has been suggested that, for compression tests, the edge of the cubic specimen should be at least seven times the size of the cell one [36].

Corrosion tests can also be performed for the evaluation of foam resistance in corrosive working environments, but no specific standards have been reported for cellular materials [12].

Density measurements can be performed by means of weight and volume measurements, even on complex shaped samples, paying attention to avoid water penetration in foam pores when using the Archimedes' principle application [12]. Furthermore, one must consider the presence, type, and thickness of the surface skin. These measurements are extremely important for the determination of the relative density of the foam, which affects the majority of foam properties when compared to the ones of the dense metal.

Penetrating liquids can be successfully used for the investigation of surface defects (holes and cracks) by visual inspection [12], while X-ray radiography or computed tomography are useful techniques for the 2D/3D inspection of porous materials [12], cells, and walls characteristics, as well as the presence of eventual defects, which can be visualized without sample damage. Moreover, the continuous acquisition of 3D tomographic images has been recently used for the in-situ investigation of bubble generation, growth, and coalescence in aluminum foams, during the foaming process [37].

Multifrequency electrical impedance measurements can also be used for the investigation of relative density and pore size because the excitation of the material through the application of an alternated magnetic field induces the development of Eddy currents, which depends not only on frequency and sample geometry but also on sample porosity [12].

Acoustic and vibrational properties of foams are of particular interest for their practical application and can be investigated by means of an impedance tube, in the first case, and by the analysis of sample vibration upon a known excitation without sample fixation (e.g., sample suspended with wires in order to make possible its vibration) in the second case [12].

The thermal conductivity of open-cell foams is the most studied field because of the application of these materials in heat exchangers, and the experimental measurements were performed using a guarded hot plate apparatus with Peltier modules [38] and several models for the prediction of thermal conductivity were developed and proposed [39]. In addition, thermal conductivity measurements on closed cells aluminum foams have been performed by means of the transient plane source technique, in which the element works both as a temperature sensor and heat source [40][41]. The works show a dependence of thermal conductivity on foam density and inhomogeneity.

Although many research works report the characterization of metal foams, few describe the use of these cellular materials in casting technologies and consequently the final characterization of the cast object.

The majority of the reported works use metallographic preparation and observation (optical and scanning electron microscopy) of the cross-section of the cast object. This procedure gives exhaustive information on the quality of core–shell bonding, on the microstructure of the dense shell, the foam core, and the eventual reaction layer between them, the entity of eventual core penetration by molten metal (by the evaluation of the residual porosity and the presence of dense metals in pores), and globally on the quality of the cast object. However, it is a destructive test and cannot be considered for the in-line control of casting objects.

Micro-CT analyses can be used for a non-destructive observation of core–shell interface and core integrity without sample cutting with good results, as reported in [42]. However, this technique requires complex instrumentation, time and it is expensive.

Moreover, scanning acoustic microscopy has been proposed for the non-destructive analyses of joining [43] and can be proposed for Al-foam in cast objects in order to investigate the characteristic of Al-foam–cast metal interface in a non-destructive way.

Finally, some of the characterization techniques described above for metal foams, such as density measurements, mechanical tests, corrosion tests, electrical impedance and thermal conductivity measurements, as well as the use of penetrating liquids, can be reasonably adapted to cast objects containing a metal foam core if it is possible to obtain representative samples suitable for the tests. Their application is not yet reported to the best of our knowledge, but can be further investigated for the use of metal foam cores in casting technologies.

In addition to experimental techniques, for the characterization of metal foams as well as of metal foam containing structures, numerical models were proposed.

Most of the works use mathematical models to study the static and dynamic behavior of metal foams [44][45][46][47][48][49][50][51][52][53]; thermal properties have been investigated by these routes as well [54].

From the point of view of the material geometrical simulation, both regular cell size/shape [39][46] and random cell size/shape [45][50] have been proposed. Random models are generally closest to the real foam structure. Some works also report model construction from Computed Tomography (CT) images of real foam samples through proper image elaboration routes [49][52]. Finally, some papers propose not only the modeling for foam samples but also for more complex structures containing metal foams such as sandwiches [48], joined cantilevers [51], and foam-filled tubes [53].

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