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Characteristic compressive properties of hybrid metal matrix syntactic foams

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ABSTRACT

Hybrid metal matrix syntactic foams (hybrid MMSFs) are particle reinforced composites in which the reinforcement is the combination of more than one grade of hollow spheres. The difference between the spheres can be in their chemical composition, dimension, physical properties etc. In this study AlSi12 matrix hybrid MMSFs with monomodal Globocer (Al_2O_3 and SiO_2 based ceramic) and Globomet (pure Fe) reinforcements were produced by pressure infiltration. The investigation parameters were the ratio of the hollow sphere grades and the aspect ratio of the specimens. Microstructural investigations showed almost perfect infiltration and favourable interface layer, while quasi-static compression tests showed that the composition of the reinforcement and the aspect ratio of the specimens have determinative effect on the characteristic properties (compressive and flow strength, fracture strain, stiffness and absorbed energy). This nature of the MMSFs ensures the possibility to tailor their properties in order to optimise them for a given application.

1. Introduction

Metal matrix syntactic foams (MMSFs) are special particle reinforced composites that consist of a metal matrix (usually some kind of Al or Mg alloy, to get maximal weight reduction) and a set of hollow, spherical particles. Most commonly the hollow spheres are built up from some sort of ceramic or metallic material and they are commercially available [1–5]. MMSFs have outstanding mechanical properties, like higher strength, stiffness and energy absorption capacity compared to other metallic foams, while their fracture strain is usually lower. Due to this, the MMSFs have promising application possibilities as lightweight parts or as hulls of public and/or military vehicles [6,7], as well as collision or vibration dampers.

In most cases MMSFs are made by stir casting or infiltration. Stir casting is cheaper and faster, but it can only produce lower reinforcement volume fractions due to hollow sphere breakage caused by mechanical stirring [8–16]. In the case of infiltration two basic methods can be separated: gravity-fed infiltration (only in the case of wetting matrix – reinforcement systems [17–20]) and pressure-assisted infiltration (for non-wetting systems). In the latter case a threshold pressure must be overcome in order to get acceptable workpieces. The threshold pressure can be calculated (estimated) [21–28] or measured [29–31]. Pressure infiltration is capable of producing MMSFs with maximal (~64 vol%) hollow sphere volume fraction and better matrix dispersion, but it requires more investment and more sophisticated equipment [29,30,32–38]. In practice, usually one kind of hollow sphere set with monomodal diameter distribution is applied as reinforcement. Only a few efforts have been published about MMSFs with bimodal hollow sphere diameter distribution [39]. Daoud [10] produced closed cell foams by gas releasing method and added hollow spheres into the ZnAl12 base metal. This hybrid foam showed ductile compressive deformation and exhibited higher mechanical strength than pure ZnAl12 foams. Xia et al. [40] produced and investigated Al99.5 based closed cell foams with different kinds and contents of ceramic microspheres in the cell walls by melt-foaming method. They showed that the microspheres have a significant effect on the strength, the deformation capabilities and the energy absorption of the foams. However – according to the best knowledge of the authors – no research results have been published about other hybrid MMSFs containing at least two different reinforcement grades. The difference between the reinforcements can be in the mean dimension, chemical composition, physical properties etc. For example, in the case of MMSFs the material of the spheres can be different: metal and ceramic hollow spheres can be combined.

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The most common loading mode of the foams is compression. Therefore the compressive properties of MMSFs have been widely studied and the quasi-static testing method has been standardised in DIN50134 [41]. Balch et al. [42,43] examined the compressive properties and the load partitioning mechanisms in aluminium based syntactic foams (ASFs). According to their results optimised properties can be reached when the matrix and hollow spheres strengths are properly matched. Dou et al. [44] performed quasi-static and high strain rate compression tests on ASFs. The results showed distinct strain rate sensitivity. Goel et al. [45] investigated the dynamic compressive properties of ASFs. They showed that the compressive strength and energy absorption attained an optimum at a given strain rate. Kiser et al. [46] investigated ceramic hollow sphere reinforced ASFs under compressive loads. Uniaxial compressive failure has been initiated at small strains through the collapse of the material within a localised deformation band. Under constrained conditions, localisation was suppressed and the flow stress increased monotonically. Different matrix (Mg and Zn alloys) syntactic foams were studied by Rohatgi et al. [47,48], Daoud [8,9] and Huang et al. [49,50]. The hollow spheres decreased the density and the foams became stiffer and stronger, than the conventional ones. Castro and Nutt [20,51] investigated the synthesis of steel matrix syntactic foams with Al_2O_3 hollow spheres. The MMSFs exhibited higher strength and energy absorption capacity than the steel foams reported previously. The compression and low-velocity impact behaviour of ASFs were also studied by the same research group [52]. Luong et al. [53–55] investigated the strain rate sensitivity of Al and Mg based syntactic foams. The MMSFs showed higher strength and higher energy absorption capability at higher strain rates. Mondal et al. [13,14] reported stir-casted ASFs behaved like high strength Al foams under compressive deformation, both at room and elevated temperature. The plateau stress decreased with hollow sphere volume fraction, following a power law relationship. Neville and Rabiei [56] produced MMSFs by a powder metallurgy technique. The materials displayed superior strength to density and absorbed energy to density ratios [17,57,58]. Palmer et al. [32] studied the compressive properties of ASFs with different size ceramic hollow spheres and various Al alloy matrices. The alloy–sphere–temperature combinations gave potential for tailoring these materials for different applications. Peroni et al. [59,60] investigated the mechanical behaviour of MMSFs made of hollow glass spheres mixed in iron matrix. The produced materials offered greatly increased quasi-static compressive strength, though at higher density. Rohatgi et al. [35] performed compressive tests on ASFs containing different volume fractions of hollow spheres. The strength and stiffness increased with the increasing density. The microstructure and quasi-static compressive mechanical properties of ASFs with Al_2O_3 hollow spheres were investigated and estimated by Santa Maria et al. [61–63] in different conditions. The peak and plateau strength as well as the toughness of the foams increased with increasing wall thickness to diameter ratio. ASFs with additional Al particles were produced by Tao et al. [64,65] via pressure infiltration. The ductility, the strength and the specific energy absorption capacity increased significantly. Different failure modes (progressive collapse and/or Griffith rupture) were observed in confined and unconfined compression as well. Wu et al. [66] performed quasi-static compression tests on ASFs: the annealed ASFs could deform plastically at a relatively high stress. A method was also established to show the relation between the relative wall thickness of the hollow spheres and the compressive strength. Zhang and Zhao [36] investigated the mechanical response of ASFs with low-cost porous ceramic hollow spheres under static and dynamic conditions. The plateau strength and the absorbed energy were largely determined by the volume fraction of Al and to a lesser extent by the properties of the hollow spheres. Zou et al. [67] studied the dynamic mechanical behaviour of ASFs produced by pressure infiltration. During the deformation process, the ASFs exhibited good energy absorption capability. Orbulov et al. [68–71] investigated the characteristic properties (compressive strength, fracture strain, structural stiffness and absorbed energy) of ASFs. In these studies, versatile combinations of matrix materials, hollow sphere grades and testing conditions (aspect ratio, test temperature, heat treatment etc.) were applied. The results showed outstanding specific mechanical properties under any circumstances.

The elastic properties of the MMSFs can be estimated via mathematical and mechanical considerations. Bardella et al. [72–75], Mondal et al. [76,77] and Marur [78–81] investigated the analytical and numerical modelling of MMSFs. Their main aim was to predict the elastic properties and to model the load transfer of MMSFs in different circumstances, including interfacial quality. The interface layer was investigated experimentally by Orbulov et al. [82–84] on microstructural scale. Chemical exchange reactions were observed and confirmed that can alter the quality of the interface layer, and through this, have a serious effect on the mechanical properties. Moreover Orbulov et al. [85,86] gave the analytical description of the behaviour of ASFs that can be applied to model MMSF parts numerically.

As it is presented above, the mechanical properties of MMSFs have been more or less widely measured, but data about hybrid MMSFs is lacking. Therefore the aim of this paper is to give detailed introduction to the mechanical and microstructural properties of hybrid MMSFs.

2. Materials and experimental methods

2.1. Investigated materials and production method

Near eutectic AlSi12 alloy (Al4047) was used as matrix material due to its low melting point (~575 °C) and low viscosity. The measured chemical composition of the matrix was 12.830 wt% Si, 0.127 wt% Fe, 0.002 wt% Cu, 0.005 wt% Mn, 0.010 wt% Mg, 0.007 wt% Zn and the remaining was Al. This composition is in the range of the standardised nominal values [87]. The total amount of reinforcement was maintained at high level (~64 vol%) that corresponds to the randomly close packed structure (RCPS [88,89]) in all cases. The reinforcement consisted of two different grades of hollow spheres (one ceramic and one metal) manufactured by Hollomet GmbH [1]. The ceramic hollow spheres (Globocer, GC) had the average diameter and wall thickness of $\varnothing 1425 \pm 42.2\ \mu m$ and $t = 60 \pm 1.7\ \mu m$ respectively, while their density was $\rho = 0.816\ g\,cm^{-3}$. The chemical composition of the hollow sphere's wall material was 33 wt% Al_2O_3, 48 wt% SiO_2 and 19 wt% $3Al_2O_3 \cdot 2SiO_2$. The metallic hollow spheres (Globomet, GM) had the similar average diameter ($\varnothing 1413 \pm 21.5\ \mu m$) but smaller wall thickness ($t = 23 \pm 0.6\ \mu m$), while the density was $\rho = 0.704\ g\,cm^{-3}$. The fracture force of GC and GM grade hollow spheres between polished plates was 22.1 ± 1.18 N and 5.1 ± 0.18 N (50 − 50 measurements) respectively, so the GC grade hollow spheres proved to be significantly stronger. The GC and GM grade hollow spheres showed brittle fracture and plastic failure, respectively. The ratio of the hollow spheres varied from 100% GC and 0% GM to 0% GC and 100% GM, in 20% steps.

The hybrid ASFs were produced by inert gas (Ar) assisted pressure infiltration (Fig. 1). First, the hollow sphere grades were hand-mixed carefully to reach uniform ratio of them throughout. This could be ensured by hand-mixing, because the density difference between the grades is quite small. The mixed hollow spheres were poured into a graphite coated carbon steel mould (height: 360 mm, cross section: $40 \times 60\ mm^2$, wall thickness: 3 mm) to the half and they were