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Open-cell aluminium foams with graded coatings as passively controllable energy absorbers

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ABSTRACT

Compared to most bulk materials, open-cell aluminium (Al) foams (OCAFs) are light-weight and can absorb a significant amount of energy in compression, e.g. during impact. When coated with nickel (Ni), OCAFs can absorb even more energy, making them more appropriate for impacts at higher velocities than uncoated OCAFs. When Ni-coated OCAFs experience low-velocity impact however, the stopping distance during the impact is small compared to that of uncoated OCAFs and hence, deceleration occurs fast. This exposes devices (and possibly human beings) protected by OCAFs to large internal forces leading to internal damage. An OCAF that combines the properties of uncoated and coated OCAFs can absorb energy during both low-velocity and high-velocity impact scenarios. This contribution introduces two of such OCAFs which are created by partially and gradually coating OCAFs. The general mechanics of the two OCAFs are revealed using experimental and numerical observation methods.

1. Introduction

Open-cell metal foams (OCMFs) can be used in a wide variety of engineering applications. They can amongst others be used as catalyst support [1,2], implant material [3], heat exchanger [4], sound absorber [5] and energy/impact absorbers [6–13]. In the future OCMFs may have the potential to partially replace the relatively heavy bulk metals used in crumple zones of cars as low-weight energy absorbers [14].

The convenient energy-absorbing properties of OCMFs in compression can be distinguished in Fig. 1(a), e. g. for the curve denoted by '50 μm'. The compressive response initially shows an almost linear regime up to a strain of approximately half of the pore size, at which a stress peak is present. Since in this almost linear regime a small number of struts already deform plastically, it is often called the pseudo-elastic regime. Consequently, the Young's modulus of OCMFs is determined based on the unloading response. At a strain corresponding to the full pore size a stress plateau is reached. The plateau continues up to a densification strain, at which all pores are compressed. This wide stress plateau is beneficial for energy absorption, as the area under the curve is roughly the energy dissipated in compression, i.e. during impact.

OCMFs owe their wide stress plateau as well as their low weight to their distinct mesostructure, which consists of relatively slim, metal struts connected in a sparse manner (see Fig. 1(b)). During the initial elastic stage of compression, most struts deform nearly elastically. The stress peak that ends the elastic stage, the so-called plastic collapse stress, is governed by the buckling and failure of one row of struts in the foam. During the stage of the stress plateau, the other rows of struts buckle and fail consecutively. When all struts have buckled and failed at the end of the compression, densification occurs and the stress grows significantly for small increases of strain [15].

OCMFs can be made of several metals and/or alloys (e.g. PtFeAlO, NiTi, Ta) [1,3,16]. This study focuses on those made of aluminium (Al) [6,9–15]. Jung et al. have shown that the energy-absorbing characteristics of OCAFs can be greatly enhanced by coating them with nickel (Ni) [11–13,15]. The Ni-coated foams are called Ni/Al hybrid foams. The process to apply the Ni-coating uses electrodeposition. OCAFs with Ni-coatings show substantially higher compressive stress–strain curves (see Fig. 1(a)). As a result, the energy absorption is significantly improved. For a coating thickness of 150 μm, the absolute energy-absorbing capacity is increased by a factor of 10 compared to the uncoated OCAF. When the energy absorption capacity is normalised for the mass increase due to the coating, the relative energy absorbing capacity of the 150 μm Ni-coated foam is increased by a factor of 2 compared to the uncoated OCAF [11–13,15].

1.1. Illustration of OCAFs as energy absorbers: frontal impact of cars

To illustrate the capabilities of Ni-coated OCAFs as energy absorbers, frontal impacts of cars are used in this study since these may relate to a

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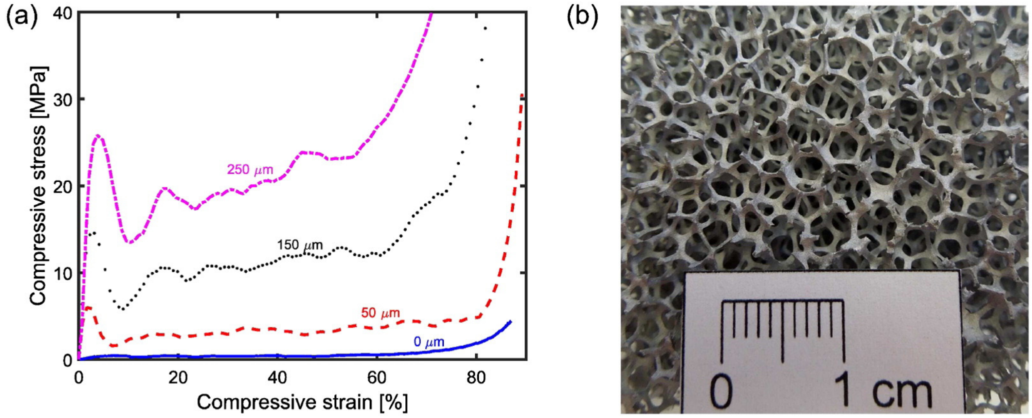

Fig. 1. (a) Compressive stress–strain responses of open-cell Al foams (OCAFs) with different coating thicknesses. (b) Microstructure of an OCAF.

wide audience. The velocity in the frontal impact test of Euro NCAP is based on research that shows that a significant proportion of accidents takes place at 55 km/h [17,18]. In the Euro NCAP tests, cars are frontally crashed against a rigid wall with 64 km/h which resembles two cars crashing frontally with 55 km/h [17]. Car manufacturers calibrate the energy absorbing tubes in cars' crumple zones to this velocity. The aim of this is to make cars perform well in the Euro NCAP frontal impact test. This means that in a frontal accident at 120 km/h, for instance, only 21% of the kinetic energy is absorbed or dissipated by the crumple zone tubes, while 79% of the kinetic energy must be absorbed by other constituents of the car and the passengers.

Hence, it may be convenient to tailor the behaviour of crumple zones, and thus the behaviour of Ni-coated OCAFs when used in cars' crumple zones, that they can absorb energy at different velocities (e.g. 55 and 120 km/h). The following consideration aims to explain why this cannot be established conveniently with the regularly-coated OCAFs of which the compressive responses are shown in Fig. 1(a).

In the following, we consider the curve denoted by '0 μm' in Fig. 1(a), of an uncoated OCAF. For means of illustration only, it is assumed that crumple zone tubes made of the uncoated OCAF with the same dimensions as standard crumple zone tubes can dissipate all the kinetic energy of a car travelling at 55 km/h. As mentioned before, 79% of the car's kinetic energy is not dissipated in this case when a frontal impact takes place at 120 km/h. A number of options can ensure that all the kinetic energy is dissipated by OCAF crumple zone tubes. First, the length and/or radius of the uncoated OCAF crumple zone tubes can be enlarged. This is not a desired solution however, as it entails significantly enlarging the front of the car.

Another option is to use a Ni-coated OCAF. It is assumed here that the response denoted by '50 μm' in Fig. 1(a) is high enough to dissipate the car's kinetic energy at 120 km/h. The dimensions of the OCAF crumple zone tube can hence remain the same. However, using the OCAF with the 50 μm coating means that during a frontal impact at 55 km/h, compression occurs only until a strain of approximately 20%. As a result, deceleration of the car -and the passengers- takes place significantly faster during an impact at 55 km/h than when the uncoated OCAF is used. Consequently, passengers' bodies are exposed to large internal forces, increasing the possibility of injuries.

1.2. Scope of this work

A more convenient alternative would be to combine some of the responses in Fig. 1(a) in one OCAF. This may be done by only partially coating OCAFs or gradually coating OCAFs. To the best of the authors' knowledge this cannot be incorporated by manufacturing uncoated OCAFs with functionally graded densities as the manufacturing process does not allow this. This work focuses on new hybrid OCAFs with partial Ni-coatings and with gradually increasing coatings. The aim of the work is not only to show experimentally established compressive stress–strain responses of OCAFs with partial coatings and gradually increasing coating thicknesses, but also to experimentally and numerically expose the general mechanics that govern their compressive behaviour. Another aim is to show in general lines how these foams can be employed to form passively controllable energy absorbers. For the latter aim, cars' crumple zones function as an exemplary illustration, but many other applications can be imagined. At the moment, OCAFs can actually not absorb the same amount of energy as crumple zone tubes. OCAFs do show qualitatively the same compressive stress–strain responses as crumple zone tubes, including the plastic collapse stress [19].

The outline of this contribution is as follows. First, materials and experimental methods are explained. Then, the general use of OCAFs as energy absorbers in cars is discussed with the focus on the limitations of OCAFs with a single coating thickness. Subsequently, the results of compression tests on partially and gradually coated OCAFS are presented and the advantages of partially coated OCAFs and OCAFs with gradually increasing coating thicknesses are discussed. Afterwards, the mechanics of a partially coated OCAF and an OCAF with a gradually increasing coating thickness are considered to give a general understanding of the mechanics. This general understanding aims to help to tailor partially coated OCAFs and OCAFs with gradually increasing coating thicknesses in the future. Finally, conclusions are presented.

2. Materials and methods

2.1. Partially and gradually coated OCAFs

Electrodeposition is a common technique for the coating of electrically conductive structures with metals and alloys. In this work cubic samples of open-cell Al foams (OCAFs) ($AlSi_7Mg_{0.3}$, Celltec Materials, Dresden, Germany) with an edge length of 40 mm and a pore size of 10 ppi, were coated by direct current plating with nanocrystalline Ni with a crystallite size of 50 ± 8 nm. The OCAFs have an average density of 0.147 g/cm^3 with a standard deviation of 0.021 g/cm^3. The size of the pores is around 4.5 mm and the struts have a triangular cross-section with a triangle edge length of approximately 0.5 mm. A commercial Ni sulfamate electrolyte (Enthone GmbH, Langenfeld, Germany) with a Ni content of 110 g/L Ni was used at a pH of 3.8 and a temperature of 40 °C. To obtain a qualitatively good coating, the pretreatment steps of pickling and electroless plating preventing the Al from dissolving in the acid Ni electrolyte have been performed according to the existing literature [20]. To guarantee a homogeneous coating over the cross-section, a cage-like anode filled with Ni pellets (Ampere GmbH, Dietzenbach, Germany), as described by Jung et al. [12,13], was used.

In contrast to the state of the art in fully coating OCAFs with nickel and nickel alloys [20–22] or with copper [23–25], the OCAFs in this work were only partially coated. Each partially coated OCAFs sample