Acta Materialia 102 (2016) 38–48

Contents lists available at ScienceDirect

Acta Materialia

journal homepage: www.elsevier.com/locate/actamat

Micromechanical characterisation of Ni/Al hybrid foams by nano- and microindentation coupled with EBSD

A. Jung [a,*], Z. Chen [a], J. Schmauch [b], C. Motz [c], S. Diebels [a]

[a] Saarland University, Lehrstuhl für Technische Mechanik, Campus A4.2, 66123 Saarbrücken, Germany
[b] Saarland University, Lehrstuhl für Experimentalphysik, Campus D2.2, 66123 Saarbrücken, Germany
[c] Saarland University, Lehrstuhl für Experimentelle Methodik der Werkstoffwissenschaften, Campus D2.2, 66123 Saarbrücken, Germany

ARTICLE INFO

Article history:
Received 18 May 2015
Accepted 10 September 2015
Available online 29 September 2015

Keywords:
Open-cell metal foams
Hybrid metal foam
EBSD
Nanoindentation
Microindentation
Micromechanical characterisation

ABSTRACT

Metal foams are a very interesting class of cellular materials that is often used for lightweight construction or as energy absorbers. Ni/Al hybrid metal foams are a new and innovative composite foam material, consisting of nano-nickel coated aluminium foams. Since the mechanical properties of foams are strongly related to their microstructure, in Ni/Al hybrid foams, the coating is an additional degree of freedom affecting the mechanical properties of the foams. For meaningful simulations of the material behaviour, a detailed knowledge of the material properties of both the coating and the aluminnium struts is necessary.

In this study, the micromechanical material parameters of Ni/Al hybrid foams are evaluated by means of nanoindentation and microindentation of the Ni coating and the Al struts. The indentation methods were coupled with electron backscatter diffraction (EBSD) in order to combine the determined parameter with the local grain structure.

1. Introduction

The increasing demand for lightweight and energy absorbing materials leads not only to searching for new materials but also to the development of new design concepts, where already well known materials are be used in the form of special structures. In this context, foams and other cellular structures are known to combine many interesting physical and mechanical properties [1]. Open-cell metal foams are bionic, lightweight cellular materials mimicking the construction elements of bones [2]. Based on their special microstructure (cf. Fig. 1) leading to a specific micromechanical deformation mechanism, metal foams can absorb a significant amount of energy in compression, e.g. during impact and thus can be used as energy absorbers [1]. Due to their high porosity, metal foams have a high stiffness, but only about 10% of the weight of a bulk material. Recently, it has been shown that coating of open-cell metal foams to build up composites can significantly improve the stiffness, strength and energy absorption capacity [3–7]. Due to their good properties, most work has been done on Ni/Al hybrid foams, consisting of aluminium foams coated with nickel or nickel alloys [3,4,8]. The coating is performed by the electrodeposition of nanocrystalline nickel. The hard facing nickel coating on the aluminium struts significantly improves the stiffness and energy absorption capacity of the two-phase Ni/Al hybrid foams by strengthening the struts against bending and buckling. Due to their worse mechanical properties in comparison to Ni/Al foams, Cu/Al hybrid foams are of more interest for applications as heat exchangers [9–11]. The field of nanocrystalline coated metal foams and nano hybrid foams, respectively, is a very new research area, in which there is still a lot to do to earn a better understanding of these highly innovative materials.

Metal foams in general are microheterogeneous materials, which can be divided into three hierarchical levels (see Fig. 1). This is called the macro-meso-micro (MMM) principle. The macroscale deals with complete components and samples with application-oriented sizes. The mesoscale is governed by several pores, while the microscale is governed by single struts. The macroscopic stress-strain response in compression of metal foams can be divided into three regions. First, there is a linear elastic regime, which is characterised by the elastic deformation of single struts. The elastic region is followed by a distinct plateau with nearly constant stress arising due to the local bending and buckling of the struts causing a plastic dissipation of the kinetic energy. This local destabilisation

* Corresponding author.
E-mail address: anne.jung@mx.uni-saarland.de (A. Jung).

http://dx.doi.org/10.1016/j.actamat.2015.09.018
1359-6454/

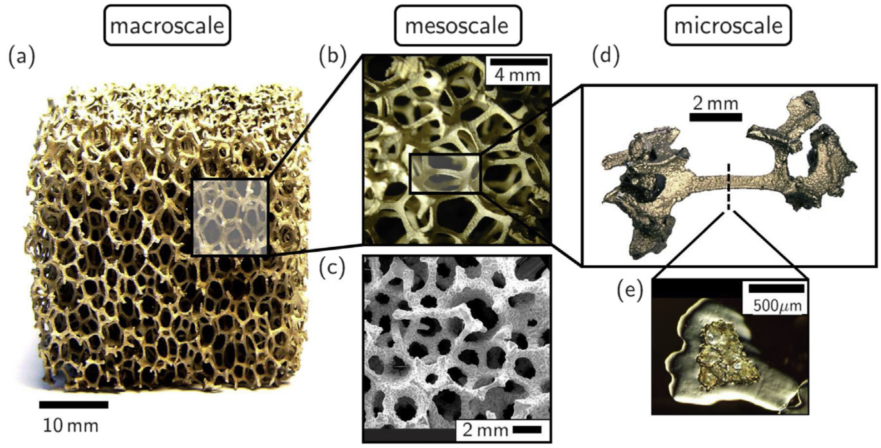

Fig. 1. Hierarchical scales of Ni/Al hybrid foam and their components. (a) 10 ppi Ni/Al hybrid metal foam, (b) optical microscopy image and (c) scanning electron microscopy (SEM) image of the pore structure, (d) single strut with the node sections and (e) cross section of a Ni/Al hybrid strut with a 200 μm thick Ni coating.

leads to the successive collapse of pore layers and hence to the formation of localised deformation bands. After the collapse of all pore layers, due to densification and the mutual contact of the struts, the plateau is followed by a steep increase in stress [2,12,13]. Hence, the global macroscopic properties strongly depend on the mesostructure (shape, size and distribution of pores) and the micromechanical properties of the struts [14–16]. A detailed knowledge of these two factors is inevitable for a reliable material simulation of these materials.

Open-cell aluminium foams are commonly produced by an investment casting technique [1]. Different cooling rates, micro stresses and the large surface to volume ratio are responsible for different grain structures and grain sizes and hence large differences in the properties of bulk materials compared to the real properties measured at single struts. The properties of single struts are higher than the bulk properties [14–16]. In the case of Ni/Al hybrid foams, both the properties of the strut material and the nickel coating govern the mechanical properties of the hybrid foams. As a result, for the development of reliable material models for hybrid metal foams, it is crucial to determine the micromechanical material parameters on single struts and on the coating as well.

Micromechanical testing of materials is an emerging field in material testing. It is very challenging and up to now, only a small amount of work has been done on the micromechanical testing of cellular materials [17,18]. Young's modulus and the yield strength of single struts of aluminium foams can be determined by nanoindentation [15–17,19,20] or microtensile tests [21,22]. On the new and promising Ni/Al hybrid foams, significantly less research has been done on the micromechanical testing of single struts or the single phases of the Ni/Al hybrid foams [6,23]. Jung et al. [6] outlined in a first study that the mechanical properties of the electrodeposited coating do not only depend on the deposition process, but also on the foam structure. The electrodeposition on metal foams is strongly limited due to mass flow diffusion problems [4,8]. This significantly influences the grain size and grain structure of the deposited metal. Since the electrodeposition process leads to a columnar grain growth, the grain structure is further strongly affected by the curvature of the struts and the microstructure as well.

For the multiphase hybrid metal foams, nanoindentation and microindentation are the only methods to determine the exact micromechanical properties of the single phases like the foam and the coating of the composite. In this study, we determine the micromechanical material parameters of Ni/Al hybrid foams by means of nanoindentation (NI) and microindentation (MI) coupled with electron backscatter diffraction (EBSD) in order to gain information about the local material parameters as function of the grain structure. According to the small indenter size, nanoindentation can only give hints at the real material measures, hence we performed a combination of nano- and microindentation to reveal reliable micromaterial parameters for both the aluminium alloy of the strut and the nickel coating of the new innovative Ni/Al hybrid foams.

2. Materials and methods

2.1. Synthesis of Ni/Al hybrid metal foams and sample preparation

In this study, Ni/Al hybrid foams consisting of aluminium alloy foams ($AlSi_7$ $Mg_{0.3}$, 15 $\times$ 15 $\times$ 15 mm^3 from Celltec Materials, Dresden, Germany) with a pore size of 10 ppi (pores per inch) and a coating of 150 μm nickel are investigated. The Ni/Al hybrid foams have been produced by the electrodeposition of nanocrystalline nickel with a crystallite size of about 50 nm (measured by X-ray diffraction), using direct current plating. A commercial nickel sulfamate electrolyte (Enthone GmbH, Langenfeld, Germany) with a nickel content of 110 g/L nickel was used at a pH of 3.8 and a temperature of 40 °C. For a qualitatively good coating on the aluminium, the pretreatment steps of pickling and electroless plating preventing the dissolution of the aluminium in the acid nickel electrolyte have been performed [8]. According to Jung et al. [5,24], a cage-like double-walled cube filled with nickel pellets from Ampere GmbH, Dietzenbach, Germany was used as sacrificial anode to guarantee a quite homogeneous coating.

For the EBSD, nanoindentation and microindentation measurements, a very smooth surface is needed. The surface preparation method to get a smooth surface at the nanoscale is essential for high-quality results. Based on charging problems in the EBSD measurements using scanning electron microscopy (SEM), the foam samples were not embedded in a resin. The most care in the surface preparation has to be done for the nanoindentation tests. Here, as a result of the very different hardness of nickel and aluminium, a different treatment for the nickel and the aluminium tests was needed. A mechanical polishing using grinding paper from 320 grit to 1200 grit was firstly carried out. After that, the