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Mechanical characterization of open cell aluminium foams reinforced by nickel electro-deposition

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ABSTRACT

The present study focused on the improvement of mechanical properties of open cell aluminium foams thanks to electro-deposition of nickel. In the first phase of the work, the parameters for the electro-deposition of nickel were optimized in order to increase the mechanical properties of these cellular materials. Different values of deposition currents and times were considered to vary the amount of nickel deposited. The performance improvement was evaluated by means of stress–strain curves. Strains were measured using a specifically developed optical extensometer with a resolution in strain of 14.1 micro-strains. A very low compression speed was set to provide a good temporal resolution given the type of camera used. Mechanical properties of aluminium foams coated by nickel or copper were compared according to the defined procedure to identify the effect of material and thickness of the coating. Stiffness was found not to be significantly affected by the electro-deposition of copper or nickel. On the contrary the maximum specific stress has been dramatically improved by the nickel coating.

1. Introduction

During the last 40 years, important research effort has allowed to create foam from any material (polymers, metals, ceramics, and glasses). This work also helped to better understand these cellular materials, which are now used in many applications [1,2], from vibration control to thermal exchanger via bio-compatible inserts, filters, electrodes, shock absorbers [3], and even artificial wood [4]. The field of applications covers the automotive, aerospace or nuclear industries [5,6]. Metallic foams are widely used in engineering thanks to their higher specific stiffness compared to monolithic equivalent. They can be used as stiff and light fillers in structural components or be actually part of the structures. Also open-cell metallic foams are more and more widely used as heat exchangers thanks to their very high thermal conductivity [7,8].

There are three main ways of manufacturing metallic open-cell foams: casting, metallic deposition, and powder metallurgy [9]. It is possible to create foams by casting using several techniques: bubbles can be injected into or created using a blowing agent in melted materials, casting around granules laid in the casting mold which would then be removed, or by investment casting. The second way, based on metallic deposition consists in applying a metallic layer onto a 3D mesh. Powder metallurgy comprises also several techniques. The slurry foaming technique consists in firing a whipped mix of fine metal powder, foaming agent, and organic vehicle. Loose powder can be used to create foams using sintering: contacts between particles are established and grow by the action of capillarity or surface tension forces. It is also possible to combine both previous techniques and heat at different temperatures to allow each process to happen successively [4,10].

Taking advantage of the good mechanical and thermal properties of these foams, it is possible to produce more compact heat exchangers by partially merging the structural function into the heat exchanger using coated metallic foams. The first article to study the effect of *Ni–W* coating on the mechanical properties of aluminium foams was published in 2008 by Boonyongmaneerat et al. [11]. They report that the increase of density directly leads to an increase in mechanical properties. More recently, copper coating was also found to improve the energy absorption capacity [12]. Models were also derived and compared to experiments to predict the improvement of mechanical properties thanks to the metallic coating [13,14]. However, the presence of correction coefficients that do not hold a physical meaning [13], limits their applicability. Nevertheless, they can be useful to study the effect of the parameters on the mechanical behavior. The effect of coating on the behavior under impact has also been studied [15,16]. It was found that the coating greatly improves the impact resistance and energy absorption thanks to the increase in buckling load of the individual struts. Work was also conducted on understanding the limit [17]. To improve the mechanical behavior other processes can be applied such as annealing [18] which significantly enhance the energy absorption capacity.

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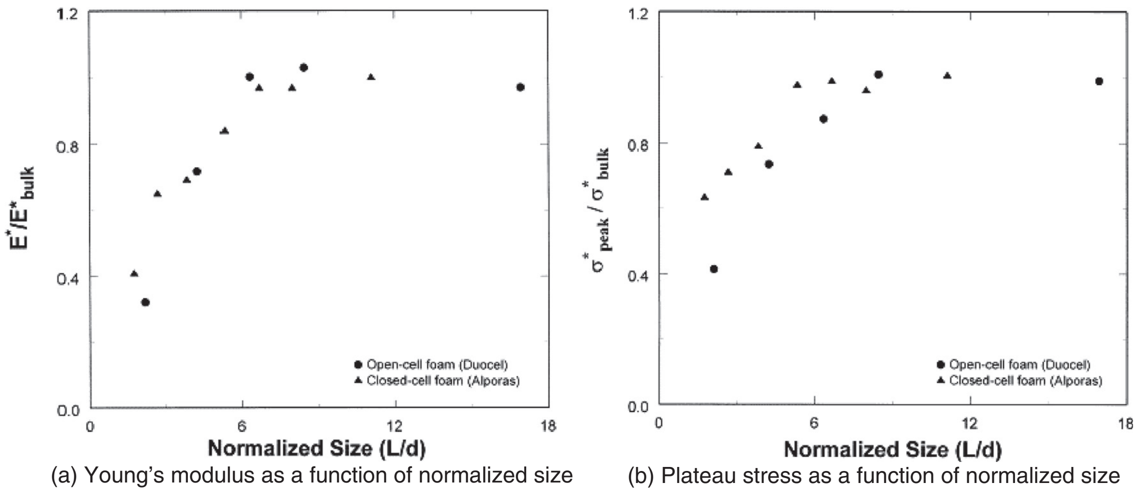

Fig. 1. Effect of sample's dimension to cell size ratio on (a) Young's modulus and (b) plateau stress [22].

A first study from the same research group looked at a single metal (*Ni*) for the coating and used the cross-head displacement to derive the strains in the sample [19]. The aim of the current work is to look at the influence of the coating materials in their pure form and electro-deposition parameters on mechanical properties using a non-contact strain measurement technique and to contribute to the better understanding of a new group of hybrid open-cell foam materials. In the first part of the study, the electro-deposition of nickel was optimized in order to increase the mechanical properties of these cellular materials. Subsequently, the performance of aluminium foams coated by nickel or copper electro-deposition was compared based on the strains obtained by the custom implementation of optical extensometry. Coppering was taken into account in this work since it is often used as an intermediate step before further deposition and it greatly improves the thermal properties, fundamental in many applications of the foams [20]. This simple and inexpensive methodology allows to realize a uniform layer of nickel that improves the mechanical properties of aluminium foams and the resistance to aggressive environments. The proposed characterization technique focused on compression properties of foam, at the macro-scale, as described in the following section.

2. Compression properties of aluminium foams and their identification

Mechanical properties can be defined at multiple scales. The cellular level where each individual strut is a structure subjected to different loading conditions relies on the mechanical properties of the base material and the geometrical definition of the struts. The typical dimension is in the order of tenth of cell size or lower. This level corresponds to the micro-scale and will not be studied in this work. The macro-scale considers the material as homogeneous therefore the typical dimension is around few cells. This work will focus on this last scale.

Compression tests are generally performed on prismatic or cylindrical specimens having a height-to-thickness ratio higher than 1.5. To obtain accurate results, extensometers mounted on the specimens should be used. A typical stress–strain curve of a uniaxial compression test presents three zones. The first is the elastic region which is nearly linear. Then there is the stress plateau. It is caused by the plastic bending of struts causing the progressive crushing of the foam. Finally, the last region corresponds to the compaction of the foam [1,21].

Because of the non-linearity in the so-called elastic region, the Young's modulus must be extracted using the slope of an unloading step. This unloading step must be made at around 75% of the compressive strength [4]. The compressive strength is the peak value in the stress–strain curve. Furthermore, grease should be applied on the loading platens to reduce frictional effects. Otherwise stress concentrations may arise at the surface of contact with the platens reducing the strength. Because of the heterogeneity of the foam, it is not uncommon to have variability in the properties, up to 30% for the Young's Modulus and 15% for the strength.

Because of the cellular structure, guidelines must be followed when determining the sample's dimensions and when cutting the samples. Andrews et al. [21,22] showed that the ratio between sample's dimension and cell size must be at least seven as illustrated in Fig. 1. The sides of the specimen are free whereas the two ends of the sample are in contact with the loading platens. The cells located near the free surfaces are less constrained than the ones in the bulk and this results in a smaller contribution to the stiffness and strength. The material therefore seems softer. When cutting the samples, a diamond saw, an electric discharge machine, laser cutting or chemical milling should be preferred over using a bandsaw. Because the latter produces more ragged surface and induces damage in the foam, the identified properties will be reduced [4].

3. Materials and methods

3.1. Samples

As imaging devices have been used, the samples are rectangular parallelepipeds. It provided flat surfaces solving potential issues with the depth of field. The height and width of the sample are 30 mm and 20 mm, respectively. They have been cut from 20 mm thick panels using a bandsaw. As this study aims at comparing the properties of samples produced following the same methodology, the reduction of properties due to the machining process can therefore be considered as constant between the samples and ignored. The aluminium foam used in this study is the ERG Duocel with 10 pores per inch. This type of

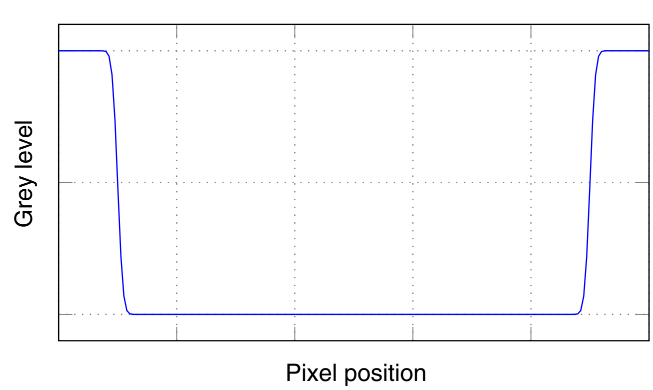

Fig. 2. Gray level profile as seen by the camera.