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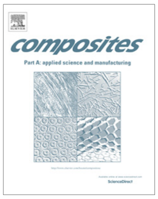

# Strain-rate effects in Ni/Al composite metal foams from quasi-static to low-velocity impact behaviour

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ABSTRACT

Metal foams are used as absorbers for kinetic energy but predominantly, they have only been investigated under quasi-static load-conditions. Coating of open-cell metal foams improves the mechanical properties by forming of Ni/Al hybrid foam composites. The properties are governed by the microstructure, the strut material and geometry. In this study, the strain-rate effects in open-cell aluminium foams and new Ni/Al composite foams are investigated by quasi-static compression tests and low-velocity impact. For the first time, drop weight tests are reported on open-cell metal foams, especially Ni/Al composite foams. Furthermore, size-effects were evaluated. The microstructural deformation mechanism was analysed using a high-speed camera and digital image correlation. Whereas pure aluminium foams are only strain-rate sensitive in the plastic collapse stress, Ni/Al foams show a general strain-rate sensitivity based on microinertia effects and the rate-sensitive nano-nickel coating. Ni/Al foams are superior to aluminium foams and to artificial aluminium foams with equal density.

## 1. Introduction

Metal foams are a very interesting class of bio-inspired materials. As a result of their high stiffness to weight ratio, metal foams are used as lightweight construction elements. Due to the special shape of their load deflection curve, they are capable of absorbing large amounts of energy at a nearly constant stress. As a result foams are widely applied in transportation, aerospace, packaging and defence industry.

Foams are microheterogeneous materials, which can be described on three different hierarchical scales. The macroscale deals with complete components and specimens with application-oriented sizes. The mesoscale is governed by several pores, whilst the microscale is governed by single struts. In macromechanical tests, the stress–strain curve of metal foams can be divided into three stages. First, there is a linear elastic regime. On the microscale, this is characterised by the elastic deformation of single struts. The elastic regime is followed by a distinct plastic flow plateau with nearly constant stress. Based on the local bending and buckling of the struts, in the plateau regime, a plastic dissipation of kinetic energy can be observed. On the mesoscale the plateau is formed by the successive collapse of pore layers leading to localised deformation bands. If all pores have collapsed, due to the densification and the mutual contact of the struts, the plateau is followed by a steep increase in stress [1–3].

Based on this special deformation mechanism with the build-up of a nearly constant stress plateau over a wide range of strain, the main application field of metal foams is energy absorption. They are used as crash absorbers in cars and trains, and in the packaging industry. Further applications see open-cell metal foams as energy absorbers in case of ballistic impacts and blast loading for industrial, military and civil structures in the form of space debris shields [4,5], against bird strike [5], claddings [6] and armour systems [7–10]. These applications all involve dynamic loading of the foams but material characterisation and testing has been almost entirely carried out at quasi-static rates.

Open-cell foams are of special interest, since based on their open porosity, they give the opportunity for a flow of a fluid through the foam structure or for a filling of the structure with a further material to provide multi functionality. A drawback of open-cell foams is the small energy absorption capacity in comparison to closed-cell foams or metal matrix syntactic foams [11–14]. By coating open-cell foams, it is possible to modify the mechanical properties like the energy absorption capacity [15–19]. Ni/Al composite foams, also referred to as Ni/Al hybrid metal foams,

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are composites based on aluminium foams coated with nanocrystalline nickel. The coating is performed by electrodeposition [15,16,20]. 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.

According to Deshpande and Fleck [21] and Zhao et al. [10], respectively, there are four reasons for the strain-rate effects of cellular materials. These comprise a rise in pressure of the pore fluid, the strain-rate sensitivity of the strut material, enhancement of shock waves and microinertia effects. The rise in the pressure of the pore fluid is only an issue for closed-cell foams or fluid-filled open-cell foams [10], where the pore fluid deforms or moves slower than the foam framework. Shock propagation and enhancement become significant at high impact velocities of about 50 m/s. Based on the micromechanical model of Gibson and Ashby [22], the material properties of foams can be expressed by the correlated property of the strut material, e. g. the compressive strength of the strut material and a power law of the relative density, which is defined as the ratio of the foam density and the density of the strut material. The only rate-dependent measure in this equation is the compressive strength of the strut material. As a result, if none of the other three reasons for the strain-rate sensitivity are valid, foams are only strain-rate sensitive if the bulk material shows a distinct rate effect. Under this assumption, it becomes clear that the strain-rate effect of open-cell aluminium foams is negligible, because aluminium has a very small rate sensitivity [23], also a significant effect on open-cell magnesium foams with the large rate dependence of magnesium can be observed [24]. A significant effect in strain-rate sensitivity of cellular materials made of non-rate sensitive materials is caused by the microinertia of the framework. According to Calladine and English, microinertia effects arise in cellular materials if two different deformation modes exist [25–27]. Under dynamic loading, a change in the deformation mode occurs and it changes from a more bending-dominated quasi-static deformation mode to a dynamic mode. The dynamic deformation mode is characterised by a delayed buckling of the struts and hence shows a stretching-induced additional amount of energy dissipation [25–27].

The dynamic testing of cellular materials is, to a large extent, related to polymer foams [28]. The small amount of investigations on metal foams have been mainly conducted by the SHPB method [16,10,29–31]. This comprises strain-rates between $10^3$ and $10^4\,\mathrm{s}^{-1}$ and is a dynamic strain-rate regime. Very limited data on metal foams are currently available for the mechanical properties at medium strain-rates used in the automotive and aerospace industries. Only a handful of papers deal with the drop weight testing of open-cell foams performed as compression tests [30,32–37] and not as indentation tests [28,38–43]. Drop weight tests belong to a lower-velocity impact regime with strain-rates between $10^1$ and $10^3\,\mathrm{s}^{-1}$, covering the strain-rates that would typically occur during car crashes. In general, a dropping hammer or weight strikes a specimen and causes dynamic loads. The advantages of drop weights in comparison to other methods are easy implementation, control and good repeatability. Before the test, the drop weight has the potential energy $E_{pot} = mgh$, and just before the impact, the kinetic energy $E_{kin} = \frac{1}{2}mv^2$. The drop weight is the sole contributor to the dynamic loading. Directly at the moment of the impact, the kinetic energy equals the potential energy. Hence, the impact velocity $v$ can be tailored by the relation

$$v = \sqrt{2gh}, \tag{1}$$

where $g$ is the acceleration of gravity and $h$ is the drop height. So the impact velocity and initial strain-rate are independent of the mass but the latter depends on the sample size. Only the energy depends on the mass of the falling drop weight. In contrast to quasi-static compression tests, the velocity (and therefore the strain-rate) is not constant throughout the test. The drop weight decelerates during the impact event, as the kinetic energy $E_{abs}$ is absorbed by the specimen and the drop weight achieves a residual kinetic energy $E_{kin,r}$ after the impact. The energy absorbed by the specimen during the impact, $E_{abs}$, can be calculated using the impact velocity $v_0$ and the residual velocity $v_r$ after the impact.

$$E_{pot} = E_{kin,0} = E_{kin,r} + E_{abs} \tag{2}$$

$$E_{abs} = \frac{1}{2}mv_0^2 - \frac{1}{2}mv_r^2 \tag{3}$$

For compression testing, $v_r$ will become zero at some time during the test. At this time, the test can be considered finished, though recoverable elastic energy in the specimen and/or test rig components may result in subsequent negative $v_r$ values.

To determine the stress–strain responses and the energy absorbed by the specimen, the velocity–time and the displacement–time history can be deduced from the force–time history recorded during the drop weight test. The acceleration–time history can be calculated according to Eq. (4)

$$a(t) = \frac{F(t)}{m}. \tag{4}$$

The velocity–time history can be determined by integrating the acceleration–time history

$$v(t) = v_0 - \int a(t)\mathrm{d}t. \tag{5}$$

And finally, the displacement–time history is calculated by integrating the velocity or the double integration of the acceleration

$$u(t) = \int v(t)\mathrm{d}t = \int \left(v_0 - \int a(t)\mathrm{d}t\right)\mathrm{d}t. \tag{6}$$

Hence, the absorbed energy results by integration of the force–displacement responds.

$$E_{abs}(t) = \int F(u)\mathrm{d}u \tag{7}$$

Juntikka et al. have investigated closed-cell polymeric foams under different temperatures and the appearance of vibrations in the signals from the drop weight tests [44]. Hamada et al. and Cho et al. have investigated strain-rate effects of closed-cell aluminium and aluminium alloy foams using drop weight tests [28,31]. Different methods to study the deformation and damage evaluation during the drop weight tests are possible. Crupi et al. have used thermographic images for the investigation of PVC sandwich foams and closed-cell aluminium foams [38], whereas Yang et al. have used digital image correlation (DIC) [45].

In this study, we investigate the effect of strain-rate on the compression of aluminium and Ni/Al hybrid composite metal foams from quasi-static to low-velocity impact loading from strain-rates of $10^{-3}\,\mathrm{s}^{-1}$ up to $950\,\mathrm{s}^{-1}$ using servo-hydraulic testing machines and drop weight tests. The micromechanical deformation mechanism for the different strain-rates is observed using digital image correlation (DIC). The experimental results can help designing metal foams with the optimal properties for a given application. They will also provide a good understanding of the deformation mechanisms of aluminium and Ni/Al composite foams and enable engineers to better utilise their energy absorption characteristics under dynamic loading.