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# New hybrid foam materials for impact protection

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ABSTRACT

The present paper investigates the dynamic compression and impact behaviour of a new class of open-cell Ni/Al-hybrid metal foams (nickel strengthened aluminium foams) in comparison to pure aluminium foams. In order to determine the characteristics of the pure aluminium and Ni/Al-hybrid foams, dynamic compression tests using a classical split Hopkinson pressure bar have been performed at strain rates up to 5000 $s^{-1}$. Whereas the pure aluminium foams show only slight strain rate sensitivity, the hybrid foams are highly strain rate sensitive. The stress strain characteristics show a change in the deformation behaviour of the foams from bending dominated failure under quasi-static compression to a failure mode induced by microinertia effects under dynamic loading with additional stretching. As a fact of this additional stretching the hybrid foams are able to dissipate more energy under dynamic loading.

Further ballistic impact tests have been performed on foam sandwich panels at impact velocities of 300 m/s. The hybrid foams show a significant improved ballistic protection performance especially in the case of elastomeric fillings. The paper outlines the possible application of Ni/Al-hybrid foams as crash absorber, security panels in case of blast and ballistic impact.

## 1. Introduction

Metal foams are a very interesting class of bio inspired light weight materials. Open-cell metal foams consist of a three-dimensional network of stochastically distributed pores and are based on large load-bearing bones like the head of femur. According to their microstructure metal foams are able to undergo large deformations at a nearly constant stress, the so called plateau stress [1,2]. This is the reason why metal foams are often used as crash energy absorber. The last decade has brought the effort for the use of metal foams as energy absorbers in case of ballistic impacts and blast loading for industrial, military and civil structures in form of space debris shields [3], claddings [4] and armour systems [5–7]. Since the material properties may significantly vary with the applied strain rate, there is an increase in interest in strain rate sensitivity of cellular materials under dynamic loading.

Whereas cellular materials with periodical morphology (e.g. honeycombs) show an increase in the compression strength of 20–50% under dynamic loading [8–10], there is no consistent strain rate dependency for stochastic cellular structures like foams. Rinde and Hoge [11] demonstrated only a marginal effect of the strain rate on the compressive strength of stiff polyurethane foams. Shim et al. [12] showed a strong strain rate sensitivity for closed-cell foams made of polyurethane. Several investigations on open-cell aluminium foams reflect a negligible strain rate sensitivity of the specific energy absorption capacity and compressive strength [13–16]. On the other hand the material properties of closed-cell aluminium foams are strongly dependent on strain rate [7,17,18]. This shows that there is need for further investigations in this topic.

Sandwich structures with aluminium foam core are good energy absorber for impact protection [19]. For the use of foam sandwich structures as space debris shields or armour material, ballistic impact experiments of sandwich panels with aluminium foam cores are used. Ballistic indentation tests are a kind of dynamic indentation test. It could be shown that fibre-metal sandwich structures with closed-cell aluminium foam core offer higher specific perforation energy than the same composites without a foam core [20]. Hou et al. [19] investigated the ballistic performance of metallic sandwich structures with closed-cell aluminium foam core as energy absorber for impact protection. Tests on open-cell aluminium foams were done by Hanssen et al. [21]. They outlined the positive influence of aluminium foam core sandwich panels in experiments and numerical simulations of the bird strike on the sandwich panels. Destefanis et al. [3] investigated composite sandwich panels of open-cell aluminium foams, Kevlar® and face-sheets of a high-strength aluminium alloy for application as Whipple Shield against the thread of high-velocity impacts of space debris on manned spacecraft. They came to the result that an

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aluminium foam as core for sandwich panels with aluminium facesheets guarantees good light weight strength and stiffness performance and that the ballistic performance is at least comparable with the one obtained for the nowadays used heavier shielding of the Columbus SWS modul.

In this study the strain rate sensitivity of Ni/Al-hybrid metal foams is investigated by quasi-static compression tests and dynamic compression tests using a split Hopkinson pressure bar. Despite of these experiments with areal load conditions, ballistic impact experiments with a point-shaped loading of the foams were performed at impact velocities of about 300 m/s. Changes in the ballistic performance between pure aluminium foams and the hybrid foams will be evaluated and illustrated.

## 2. Theory

Strain rate sensitivity is very important for materials and engineering structures that are used under high strain rate conditions. A lot of bulk materials are rate dependent which means they show different material properties at different strain rate regimes. Commonly, such materials show an increase of the strength with increasing strain rate. This behaviour arises from the microstructure. Materials are rate sensitive if dislocations or obstacles with short-range effect are thermally activated built during the deformation. At the onset of dynamic plastic deformation the strength increases as a fact of the rapid increase in dislocation density.

Up to now, strain rate sensitivity of cellular materials is not well understood. According to Deshpande et al. [14] and Zhao et al. [7] respectively, there are four known possible reasons for strain rate effects of cellular materials: rise in pressure of the pore fluid, strain rate sensitivity of the cell and strut material respectively, distribution and 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 [7]. Shock propagation and enhancement become significant at high impact velocities of about 50 m/s. Regarding micromechanical models as the model of Gibson and Ashby [8], the material properties of foams can be expressed by the correlated property of the cell wall/strut material for example the compressive strength of the strut material and a power law of the relative density $\rho_f/\rho_s$. Here is $\rho_f$ the density of the foam and $\rho_s$ the density of the strut material. The only rate dependent measure is the compressive strength of the strut material. Hence, if there is no other of the four reasons for strain rate sensitivity, foams are only strain rate sensitive, if the bulk material shows a distinct rate effect. This explains for example the negligible strain rate sensitivity of open-cell aluminium foams, because aluminium has a very small rate sensitivity [22] and the significant effect on open-cell magnesium foams with the large rate dependence of magnesium [23].

At last an important effect to explain rate effects on foams made of a non-rate sensitive material is microinertia of the microstructure. Microinertia effects in cellular materials can arise, if there exist two different deformation modes. Under dynamic loading a change in the deformation mode occurs from a more bending dominated quasi-static deformation mode to the 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 [24–26].

The main effects for strain rate sensitivity in open-cell foams as they are investigated in the present paper is the strain rate sensitivity of the strut material and microinertia effects.

## 3. Material and methods

In the present study open-cell aluminium foams ($AlSi_7Mg_{0.3}$ by m-pore GmbH, Dresden, Germany) with pore sizes of 10 and 30 ppi (pores per inch) have been used. According to a previous work [27], the foams have been used as substrate for an electrochemical coating with nanocrystalline nickel by direct current plating. A commercial nickel sulfamate electrolyte with 110 g/l Ni has been used at a temperature of 50 °C and a pH of 3.8. The exact plating procedure with the necessary pretreatment of the foams and plating setup can be found by Jung et al. [28,29]. The 10 ppi foams were coated with 150 μm nickel, the 30 ppi foams with 50 μm and 75 μm nickel respectively. Fig. 1 shows the microstructure of such an Ni/Al-hybrid foam. These Ni/Al-hybrid foams were tested under quasi-static compression, dynamic compression using a split Hopkinson pressure bar and in ballistic impact tests.

### 3.1. Quasi-static and dynamic compression tests

Quasi-static compression tests were performed at 30 ppi foams (pure aluminium foams and Ni/Al-hybrid foams) on an INSTRON 4204 universal testing machine at strain rates of about $5\cdot10^{-3}$ $s^{-1}$. In order to compare the results with the dynamic compression tests cylindrical foam samples with a thickness of 5 mm and a diameter of 20 mm were used.

Dynamic compression tests at strain rates of up to 5000 $s^{-1}$ were conducted on a classical split Hopkinson pressure bar (SHPB) apparatus. The SHPB is a common experimental technique for the characterization of materials under dynamic loading [30,31]. The SHPB consists of a gas gun and three elastic, cylindrical bars with a diameter of 20 mm. In order to guarantee a similar mechanical impedance between the bars and the foam samples, in this study bars made of Zicral® (AlZn 7075) were used. A detailed description of the used SHPB is given previously [32]. The samples had the same dimensions as mentioned for the quasi-static compression tests. The experimental implementation of dynamic compression tests using a SHPB technique causes two main problems. On the one hand, there are deviations in the results caused by a small pore size-to-sample size ratio and on the other hand due to the low strength of the foams, there is a bad signal-to-noise ratio. In order to minimize this problems large diameter of the bars has to be used [7]. In order to guarantee a sufficient number of pores over the cross section, as a fact of the small bar diameter only 30 ppi foams were investigated. Foams with a pore size of 10 ppi have to less pores over the thickness and over the cross section and hence would be strongly affected by boundary effects.

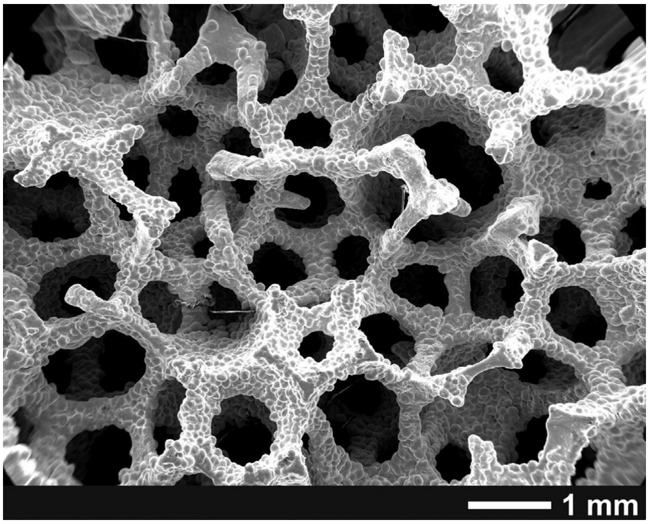

**Fig. 1.** SEM image of the cross section of a 30 ppi Ni/Al-hybrid foam.