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Improved Mechanical Properties of Nano-nickel Strengthened Open Cell Metal Foams

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ABSTRACT

Metal foams are low impedance materials which are often used as light weight construction elements, energy absorber and for structural damping. We have coated open cell aluminum foams by a nanocrystalline nickel coating via an electrodeposition process and in this way we could improve the stiffness, energy absorption capacity and the damping behavior of the foams. The mechanical behavior of the coated foams could be tuned by the crystallite size and the thickness of the coating. The foams were characterized in quasi-static compression tests as well as in dynamic compression tests, using a Split Hopkinson pressure bar (SHPB). At the optimized coating thickness of 150 µm Ni, there was an enhancement effect of the energy absorption capability of 800% for 10 ppi foams. Ballistic tests showed the applicability of the foams as splinter shield. A big opportunity of open cell metal foams is that they can be filled for example with elastomeric materials and build a composite structure.

INTRODUCTION

Metal foams are solid foams, so called metal cellular structures, containing a large volume fraction of gas-filled pores. They mimic the construction elements of bones as the spongiosa, honeycombs, cellular structure elements of wood or cork. Based on the nature of their pores, metal foams are classified in open cell metal foams with an interconnected framework of pores and closed cell metal foams with sealed pores. The ppi number is the number of pores per inch and acts as a measure to characterize the structure of open cell metal foams. According to their high stiffness to weight ratio metal foams are used as lightweight construction elements. The special stress vs. strain characteristics of metal foams is favorable for applications as energy absorber and for structural damping [1].
Open cell aluminum foams, purchased from m-pore, Dresden, were used as substrate in a coating process via electrodeposition. A detailed description of the coating process, the special conditions needed for complex three dimensional substrates as metal foams and the optimization of this coating process has been presented in previous works [2-4].

MECHANICAL CHARACTERIZATION

The stress vs. strain characteristics of metal foams is divided into three parts. The first part is the linear elastic deformation of the foam according to Hooke's law. At the plastic collapse stress the first cell of the foam deforms plastically and undergoes large deformation at a nearly constant stress, the plateau stress. This is a

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result of the bending and fracturing of the cell edges. At the densification point there is a strong rise in stress. The foam shows the behavior of a bulk material made of the same metal as the foam. The integral of the stress up to a certain strain is the amount of mechanical energy absorbed by the foam.

Quasi-static compression test

In a previous work, it could be shown that a coating of nanostructured nickel with a crystallite size of 43 nm is the best coating metal to increase the stiffness, the strength and the energy absorption capacity of open cell aluminum foams [5]. Cubic nickel coated 10 ppi foams with an edge length of 40 mm and plate-shaped 30 ppi foams with an area of 40 x 40 mm^2 and a thickness of 5 mm have been tested on a INSTRON universal testing machine under compressive loading at strain rates of $5 \cdot 10^{-3}$ s^{-1}. Based on the fact that metal foams are very complex structures and to have better statistics of the results, for each sample type the tests were carried out at least three times. Figure 1 shows the effect of the pore size (1a) and the coating thickness (1b, 10 ppi foams) on the stress vs. strain characteristics.

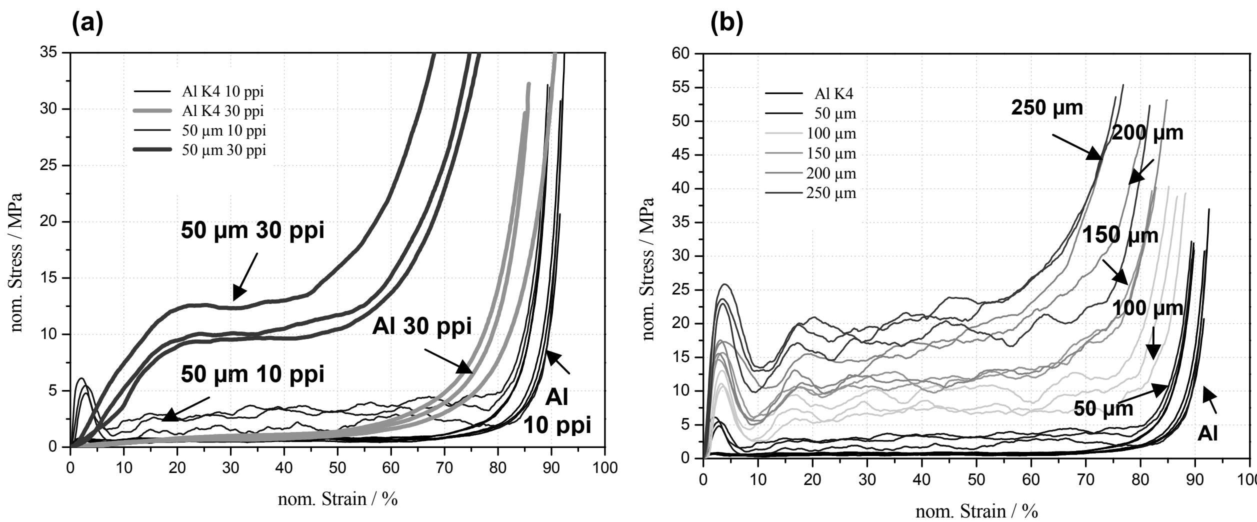

Figure 1: Effect of the pore size (1a) and the coating thickness (1b, 10 ppi foams) on the stress vs. strain characteristics.

For 30 ppi foams, the excessive stress of the plastic collapse in comparison to the plateau stress is much lower than for 10 ppi foams. Higher ppi-numbers are correlated with smaller pore sizes. The decrease in the excessive stress at the plastic collapse and the increase of the plateau stress for smaller pore sizes can be explained by the smaller bending length of the cells [6].

Figure 1b outlines the effect of an increasing coating thickness of nickel on the cubic 10 ppi foams. The plastic collapse stress and the plateau stress of the foams increase linearly with an increasing coating thickness, the densification and compression points decrease.

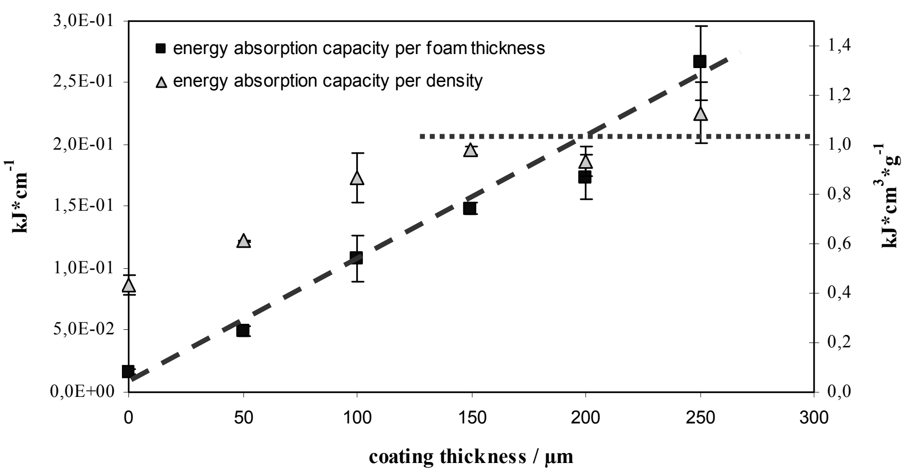

Figure 2: Dependency of the specific energy absorption capacity of nickel coated 10 ppi foams from the coating thickness.

The dependency of the specific energy absorption capacities of the nickel coated 10 ppi foams on the coating thickness is shown in figure 2. There is also a linear increase of the absolute values and the specific energy absorption capacity per foam thickness of the foams with an increasing coating thickness. But for the specific energy absorption capacity per density for coating thickness higher than 150 µm Ni the mass increase overcompensates the increase in the energy absorption capacity. Hence, there is an optimal coating thickness of 150 µm Ni. With this coating thickness the energy absorption capacity could be enhanced by factor of 8.

Dynamic compression tests

For an application as crash absorber or lightweight armor the material behavior under dynamic loading is very important. Dynamic compression tests have been performed at strain rates up to 5000 s^{-1} using a classical Split Hopkinson pressure bar (SHPB) apparatus [7]. The bars are made of Zicral (AlZn 7075) and had a diameter of 20 mm. The samples consist of 30 ppi foams with a diameter of 20 mm and a thickness of 5 mm with no coating or a coating thickness of 50 µm and 75 µm Ni, respectively. For reason of better statistics each test has been repeated at least three times.

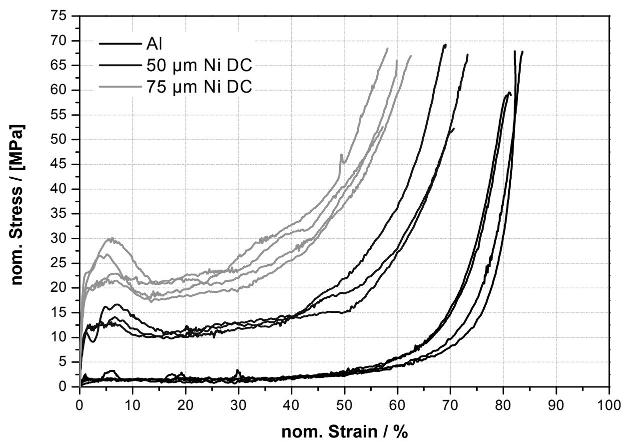

Figure 3: Stress vs. strain characteristics under dynamic loading.

Figure 3 shows the results of the SHPB tests. The plastic collapse stress and the plateau stress increase linearly with the coating thickness, the densification and compression points decrease. There is also a linear increase of the absolute value of energy absorption capacity and the specific energy absorption capacity per foam thickness (about 300% for 75 µm Ni) but there is a decrease of the specific energy absorption capacity per mass and per density with increasing coating thickness of about 3% for 50 µm Ni and 12% for 75 µm Ni in comparison to the uncoated foams.

Ballistic tests

In order to investigate the applicability of the strengthened foams as armor for slow bullets or as splinter shield ballistic tests have been performed. Metal foams show a high strength of the complete structure but only a low strength of a single strut. Compared with the abovementioned compression tests in the ballistic tests there is a more point-shape loading of the foams. Hence, the point-shape loading of the bullet has to be distributed over the foam to create a more areal loading. In this study the distribution of the loading on the foams has been done by shielding plates made of aluminum (Al 99.5%, thickness 1 mm). The ballistic tests were performed by using a steel bullet (1.4034 / X 46 Cr 13 / DIN EN 10088) with a diameter of 10 mm and a mass of 4.0 g. The bullet has been accelerated by a nitrogen driven compressed air gun. The impact velocity on the target was about 300 m/s. The tests have been observed with a high speed camera and analyzed via the residual velocity of the bullet after the perforation of the target. The nine different tested target types which are a combination of different foams and a certain number of shielding plates are listed in table 1.

Table 1: target types

Type of the target	description
Typ A	stack of 3 foams (10 ppi) with a thickness of 10 mm and 4 shielding plates
Typ B	stack of 3 foams (30 ppi) with a thickness of 10 mm and 4 shielding plates
Typ C	stack of one foam (10 ppi) with a thickness of 30 mm and 2 shielding plates
Typ D	stack of one foam (30 ppi) with a thickness of 30 mm and 2 shielding plates
Typ E	stack of 4 shielding plates with interspaces of 10 mm

The foams and the shielding plates were stacked alternatingly. Target type marked with an “N” after the type consist of coated foams with a coating thickness of 150 µm Ni for the 10 ppi foams and 75 µm Ni for the 30 ppi foams, respectively.
Figure 4 shows a comparison of the flight length of the bullet in millimeter after the perforation of the targets 400 µs after the impact of the bullet on the target. The target types C and D show a worse performance than type E which is only a stacking of the four shielding plates with interspaces of 10 mm. The target type D with the small pore structure (30 ppi) was a little bit better than the 10 ppi foam. Both for the 10 ppi and for the 30 ppi foams the energy absorbed by the deformation of the target could by increased by the nickel coating and the coated types CN and DN are better than the reference type E.

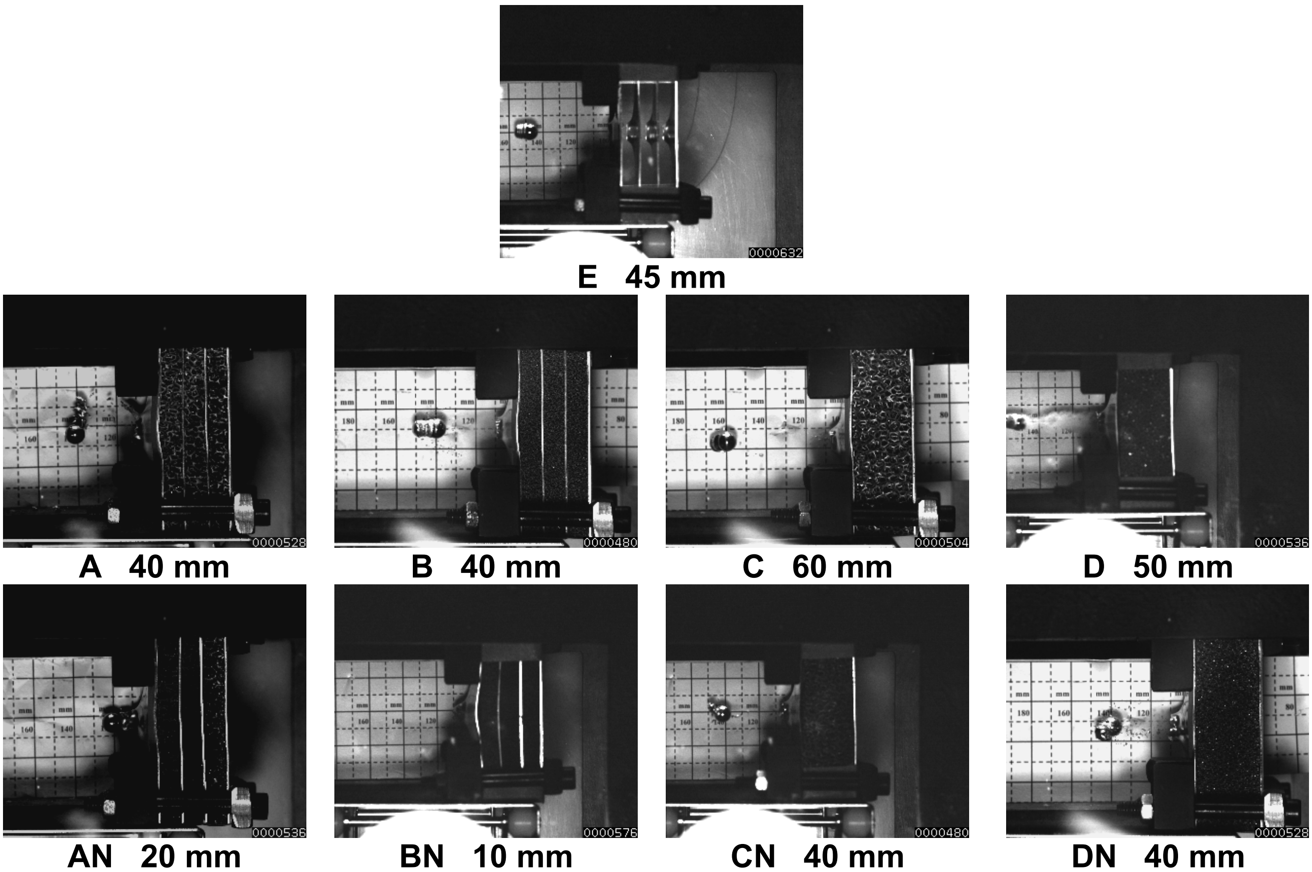

Figure 4: Comparison of the flight distance of the bullet after the perforation of the target 400 µs after the impact of the bullet on the target.

For the alternating stacking of three foams and four shielding plates there is a shorter flight distance of the bullet after the perforation which is equivalent to a higher amount of the energy of the bullet absorbed by the target structure. By coating the foams (type AN and BN) the absorbed deformation energy by the target in relation to the uncoated foams is higher than for the types CN and DN. This is a proof for the assumptions of a distribution of the point-shape loading of the energy of the bullet by the incorporation of shielding plates. The best performance as splinter shield and as armor for slow flying bullets has been shown by the stacking of three nickel coated 30 ppi foams and 4 shielding plates (type BN). The residual velocity of the bullet was so low that the bullet had not left the back of the target 400 µs after the impact yet.

CONCLUSION

Coating open cell metal foams with nanocrystalline nickel is a good way to improve the stiffness, strength and the energy absorption capacity of open cell metal foams. The coated foams show a kind of twin-wall sheet effect. The light aluminum foam only acts as support for the coating and has hardly any effect on the mechanical properties of coated foams. The stiffness, strength and stability which do also affect the energy absorption capacity do completely result from the thin, nanostructured nickel coating. Up to a critical coating thickness the specific energy absorption capacity per density increases linearly with the coating thickness,

then the mass increase overcompensates the increase in the energy absorption capacity. At the optimized coating thickness of 150 µm Ni, there was an enhancement effect of the energy absorption capability of 800% for 10 ppi foams.
The coated foams resist dynamic impact loading without a global collapse of the complete foam structure. There is no predetermined breaking point introduced by the stiff, nanostructured coating. The decrease of the specific energy absorption capacity per density and per mass outlines that under dynamic loading such strengthened foams show a higher potential for stationary applications than for mobile applications.
The ballistic tests showed that coated metal foams have potential for applications as splinter shield or protective barriers. A combination of several thin foam plates and shielding plates in a stack is necessary to distribute point-shape loading over the complete foam structure and hence to increase the absorbed impact energy of a bullet. Smaller pore sizes, which are correlated to higher ppi numbers are better than larger pores.
A big opportunity of coated open cell metal foams for a further improvement of their ability for the absorption of kinetic energies or as armor is that they can be filled for example with elastomeric materials and thus form a composite structure. This work is in progress now.

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