ALUMINUM FOAMS PROCESSED BY RAPID PROTOTYPING FOR LIGHTWEIGHT STRUCTURES

R. Vaidyanathan, M. Patterson, T. Phillips, R. Cipriani
Advanced Ceramics Research, 3292 East Hemisphere Loop,
Tucson, AZ, 85706-5013

K. A. Dannemann, A. E. Nicholls
Southwest Research Institute, San Antonio, TX 78228

ABSTRACT

The demand for faster and lighter land transportation for the troops has increased the need for more efficient structures. Sandwich panels form one type of efficient structure enabling the application of steel, aluminium or composites in the construction. Cellular metals for sandwich structures have been available for decades (Ashby 1998, Fleck 1998, and Gibson 1997), but new opportunities are emerging for two reasons. Novel manufacturing approaches have beneficially affected performance and cost (Akiyama 1987, Baumeister 1991, Jin 1990, Martin 1991, Kearns 1988, Nagel 1998), and higher levels of basic understanding about mechanical, thermal and acoustic properties have been developed (Gibson 1997, Ashby 1998). The high stiffness and yield strength achievable at low density relative to competing materials and systems creates an opportunity for ultra-light structure (Ashby 1997), especially for the Future Combat Systems, with integrally bonded dense face sheets. Large compressive strains achievable at nominally constant stress impart a high-energy absorption capacity at force levels of practical relevance for crash and blast amelioration systems (Fleck 1998). Additionally, these materials may be used effectively for either cooling or heat exchange (Evans 1998).

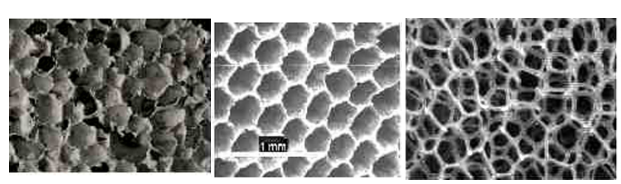
An extrusion based freeform fabrication technique (Vaidyanathan, 2000) was employed to fabricate metallic foams. The advantage of controlled pore orientation, size and ability to fabricate directly from a CAD design is that the mechanical properties could be tailored. The compressive deformation behavior of this new type of aluminum foam was assessed under static and dynamic loading conditions. Metal foam parts were fabricated by the sequential deposition of multiple discrete raw material layers. The processing methodology as well as some of the properties is presented here.

1. INTRODUCTION

One of the methods for making metallic foams involves gas expansion in foam casting. An alternative method utilizes a powder metallurgy approach and is generally a method that mixes metal powder with a foaming agent[11]. The gas pressure is derived by either a dispersed particulate such as H_2 from TiH_2, high pressure generated within an entrapped inert gas, or a gas injected into a liquid metal (Evans 1998). This mixture can then be extruded or cast into the structural shape required. Control of pore size or orientation is difficult. The powder metallurgical Fraunhofer-process (Barnhart 1998) is another alternative method used to create metallic foams. In this method, a foaming agent is added to a metal powder and subsequently mixed. This mixture can then be compacted or extruded into sheets or bars that can then be formed into the component shape using conventional deformation molding techniques. However, this process allows little control of the pore orientation and would be expensive if used to create geometrically complex parts due to the molds required.

Recently, another method termed the GASAR process has been developed (Schapavlov 1994). GASAR provides a means for controlling pore shape and orientation yet involves the use of molten metals and the injection of gases, a technically complex and expensive process. GASAR also allows the use of only one orientation in a component and the shapes are generally limited to plates, rods, or tubes.

Other researchers have also developed processes for the fabrication of metallic foam structures with oriented porosity as shown in Figure 1 (from www.metalfoam.net website). (a) shows an aluminum foam, (b) is a cellular iron-based material with cells extending in one dimension, and (c) shows a nickel sponge. However, none of these processes are capable of creating a combination of open and closed cell porosity or capable of creating components directly from CAD designs.



(a) (b) (c)

Figure 1. (a) Aluminum foam, (b) One dimensional porosity in steel foam, and (c) Nickel sponge.

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The size, distribution, and aspect ratio of close-celled porosity in a foamed material can have a direct effect on its energy absorbing and blast amelioration capability and other mechanical properties such as compressive strength (Miyoshi 1999, Mukai 1999, Dannemann 2000, 2001, Paul 2000). For example, recent experimental studies by Mukai et al. and Danneman et al demonstrated significant strain rate sensitivity for ALPORAS closed-cell aluminum foam (Miyoshi 1999, Dannemann 2000). It was found that the membrane stress, the plateau stress and the plateau strain of a closed-cell ALPORAS foam increased by an increase in the aspect ratio of cell-wall thickness against the cell-edge length and a simultaneous reduction of cell size (Miyoshi 1999). The increased energy absorption capability is directly related to the increases in plateau stress and strain (Miyoshi 1999). This effect is hypothesized to be due to the spheroidal cell walls being thicker on average and the reduced section thickness being too short to lead to cell wall buckling (Miyoshi 1999). A 50% increase in compression strength was observed at high strain rates compared to quasi-static loading (Mukai 1999). Other recent studies have shown the relative strain rate insensitivity of low-density, open-cell aluminum foams (Deshpande 2000). At least from the results reported to date for aluminum foams, it appears that higher density and higher specific strength closed cell foam materials are preferable to open celled foams or low density closed cell foams for the purposes of energy absorption. For the same density, a foam material with a higher amount of closed cell porosity will also generally have a higher compressive strength compared to an open-cell porous material, which is much weaker than a closed-cell foam material with the same amount of porosity. The strain rate dependence of yield strength for closed cell ALPORAS foam is shown in Figure 2 (Miyoshi 1999, Dannemann 2001, Paul 2000). In this figure, the y-axis in the plot is the normalized plateau stress. It is normalized based on the relative density of the specific foams.

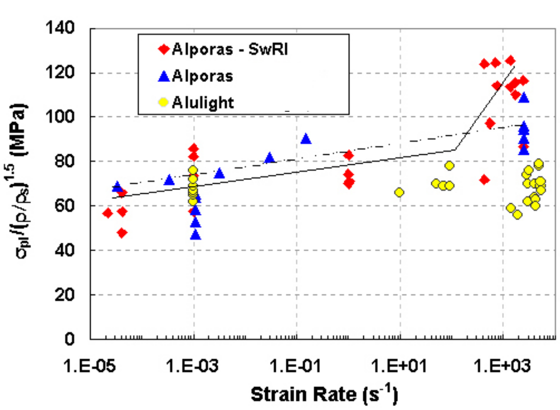

Figure 2. Normalized stress versus strain rate plot for ALPORAS and ALULIGHT foams showing strain rate dependence for the higher density ALPORAS closed cell foam.

Initial damage/deformation occurs by axial flexing and kinking of the cell walls with the extent of such deformation increasing with increasing strain. At higher strains, damage is characterized by buckling of the cell walls perpendicular to the compression axis (Dannemann 2000). Some tearing of the cell walls occurs in the buckled regions. Cell wall rupture appears to occur by a "blowout" process. The implication is that the buildup of gas pressure within the cells eventually causes some of the cell walls to rupture. The fact that the cell walls must rupture sequentially in order to permit the gas to exit the structure accounts for the strain rate sensitivity of the closed-cell structure. The above discussion clearly shows the relation between closed porosity, energy absorption and compressive strength in metallic foams. For materials derived using powder metallurgy, a certain amount of open cell porosity may be unavoidable, due to the need to remove the binder effectively. The fabrication cost of components can also be reduced further if this can be achieved directly from CAD designs. Consequently, there is an opportunity for a fabrication process that can produce complex components with a microstructure that can be optimized for the dynamic mechanical properties.

The Al foams of interest were processed using a patented Extrusion Freeform Fabrication (EFF) process (Vaidyanathan 2000). The EFF process is a versatile rapid prototyping (RP) process that provides for the fabrication of near net-shape metallic foam components from highly loaded polymer binders filled with metallic powder. Metal foam parts are fabricated by the sequential deposition of multiple discrete raw material layers. This manufacturing approach holds promise for the low cost fabrication of a wide range of metallic foam components with the desired mechanical properties. The objective of the current study was to characterize the metallic foams fabricated using the EFF process and to determine whether a strain rate effect could be obtained in these metallic foams.

2. EXPERIMENTAL APPROACH

2.1 Processing

The processing method used to fabricate the metallic foams structures was extrusion-based and is called Extrusion Freeform Fabrication. The process schematic is shown in Figure 3.

2.1.2 Extrusion Freeform Fabrication

The EFF process is a versatile rapid prototyping (RP) process that provides for the fabrication of near net-shape metallic foam components from highly loaded polymer binders filled with metallic powder. Metal foam parts are fabricated by the sequential deposition of multiple discrete raw material layers. The aluminum foam samples for this study were processed by blending metal powders (nominally 87% Al, 6.5% Mg, 6.5% Sn by weight) powders in a high-shear mixer with a molten thermoplastic blended binder that provides a combination of open and closed cell porosity in the final sintered parts. The compounded powder/binder material blend (50% binder, 50% metal powder) was pressed into feedrods, and placed in the high-pressure extrusion head barrel of the rapid prototyping machine, a Stratasys 3D Modeler, shown in Figure 3 and 4.

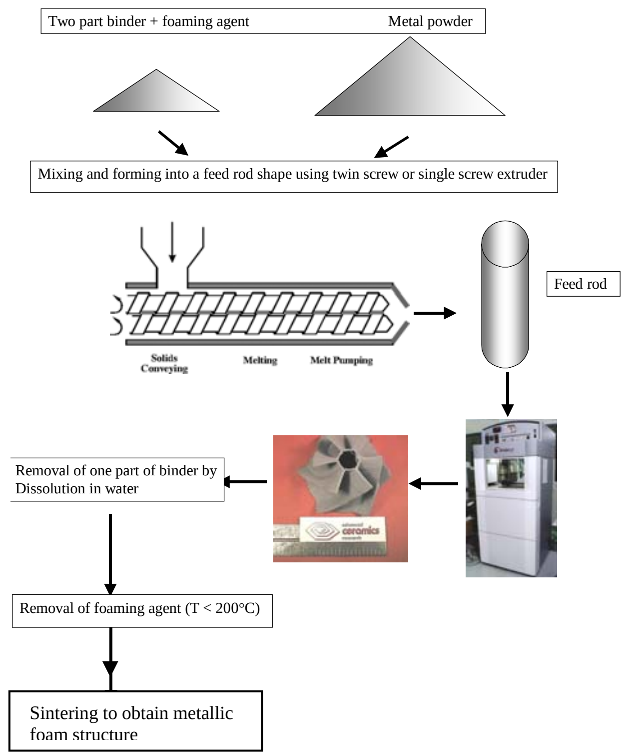

Figure 3. Schematic of the metallic foam process

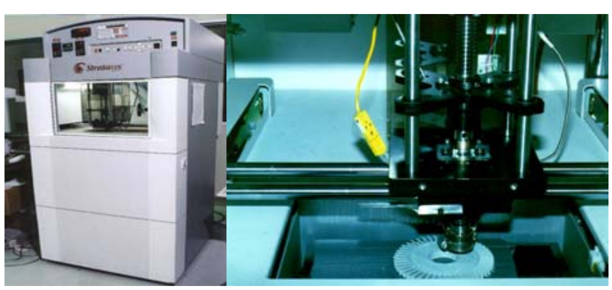

Figure 4. A Stratasys FDM™ Modeler unit retrofitted with ACR's patented high-pressure extruder head.

Following heating of the specially designed extrusion tip (0.635 mm dia), the material was extruded into individual cylinders for testing. Each cylinder was approximately 20% larger than the desired size of the compression test samples to account for the shrinkage during sintering (i.e., 2.54 cm dia, 1.5-3.0 cm long). The green aluminum cylinders were then subjected to a binder burnout process; the hold temperature controlling the pore size. Sintering and a homogenization anneal followed. The average size of the pores was between 50 and 100 µm, depending on the hold temperature during binder burnout.

For dynamic compression tests, two different types of samples were fabricated. These were [0/90]n and [0/45/90/135]n, where n is an arbitrary number of layers to obtain the necessary sample thickness. A typical transverse and longitudinal cross-section of a [0/90] sample is shown in Figure 5. The transverse cross-section shows the open-celled structure of the foam materials, while the longitudinal cross-section shows the closed-cell morphology of the individual struts on a microscale.

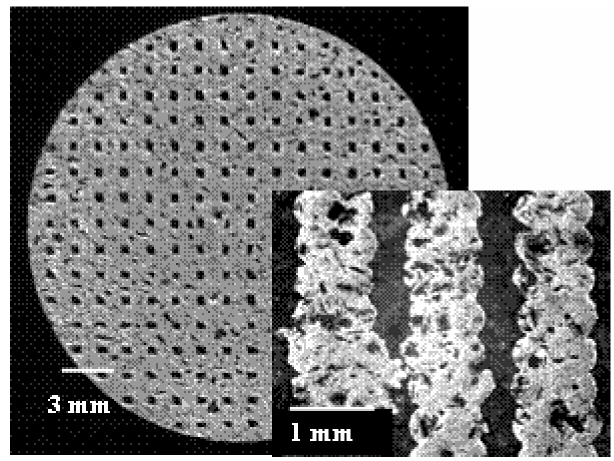

Figure 5. Cross section through the Al foam showing the 0/90 degree lay up possible and the available porosity.

Individual sample densities ranged from 1.43-1.54 g/cc for the 0/90 layup, and 1.43-1.58 g/cc for the 0/45/90/135 foams. The porosity level was approximately 55% (ρ/ρ_s = 0.53-0.58) with the 0/90 samples generally having slighter higher porosity levels.

2.2 Strength Testing

The dynamic compression response was evaluated in air using a split Hopkinson pressure bar (SHPB) system with aluminum bars, and at strain rates ranging from 600 s^{-1} to 2000 s^{-1}. Compression tests were also conducted at lower strain rates (10^{-3} s^{-1} to 4 s^{-1}) to determine the extent of strain rate strengthening, if any. The low strain rate tests were performed with a servo-controlled hydraulic test machine. The results were analyzed as a function of foam density, structure, and process conditions to determine the damage development mechanism. This information was obtained to aid in optimizing the foam material design for energy absorption.

All samples in these groups were electrodischarge machined (EDM'D) to improve the surface finish, parallelism and smoothness of the end faces. The test samples measured approximately 1.27 cm long by 2.36 cm in diameter. The sample diameter for the latter sample groups was chosen to maximize the number of open cells across the diameter within the limitations imposed by the SHPB dimensions. There were at least 12 cells across the diameter of each compression test sample. A length to diameter (L/D) ratio of approximately 0.5 was selected based on the SHPB results of preliminary samples with different L/D ratios.

The aluminum foam samples were fully compressed during SHPB testing. Several interrupted, high strain rate compression tests were also conducted to allow evaluation of deformed microstructures at a series of increasing strains. Steel spacers were used to limit the maximum strain response. Following testing, interrupted and fully loaded test samples were longitudinally sectioned and evaluated with optical and scanning electron microscopy. Compressed samples were evaluated to determine the extent of deformation of the EFF aluminum foam.

3. RESULTS

Some of the preliminary data for samples with different L/D ratios are shown in Figures 6 and 7. This was measured for two different strain rate ranges (~500-800 s^{-1} and ~1500-2100 s^{-1}). The engineering stress-strain curves obtained are shown in these figures for samples with aspect ratios of 0.5 and 1.0, respectively. The curves are overlayed for each aspect ratio grouping; sample densities are noted on the plots. Each curve represents a single test. The data appeared to scale more closely with density rather than strain rate. For example in Figure 6, the two curves with the highest peak stress have high densities (1.126 g/cc and 1.133 g/cc) compared to the other curves shown. However, the strain rates for these two curves differ substantially: 1820 s^{-1} vs. 662 s^{-1}. The red curve in Figure 6 represents the sample from this grouping with the lowest density, yet also corresponds to the highest strain rate (2122 s-1) SHPB test. This sample had the lowest peak stress values although it was tested at a high strain rate compared to the other samples.

For these materials, the effect of density was observed to be greater than the effect of strain rate. However, the preliminary results showed that there was a slight strengthening effect at higher strain rates.

The effect of sample density was further investigated for the porous metal samples. Yield strength was determined from the engineering stress-strain curves obtained. The results are summarized as a function of strain rate (Figure 8) and density (Figure 9). The strength values were normalized by density to provide a direct comparison of the response.

The results in Figure 8 show the possibility of a slight strain rate effect. However, the plots in Figure 9 indicate the effect of density is significant. Thus, there is a strong influence of density for the porous aluminum metal samples fabricated using the EFF process.

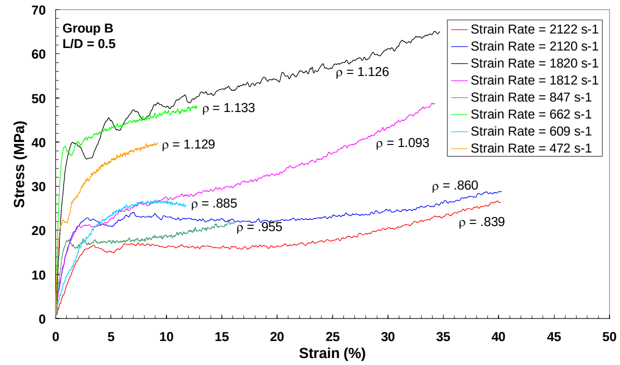

Figure 6. Engineering stress-strain response of EFF aluminum foam for the 0/90 test samples for an L/D=0.5

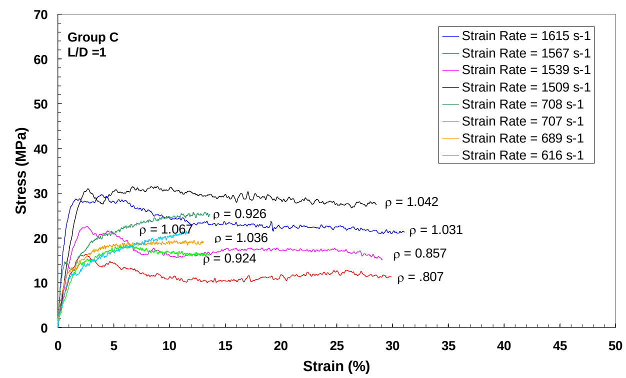

Figure 7. Engineering stress-strain response of EFF aluminum foam for the 0/90 test samples for an L/D=1.0

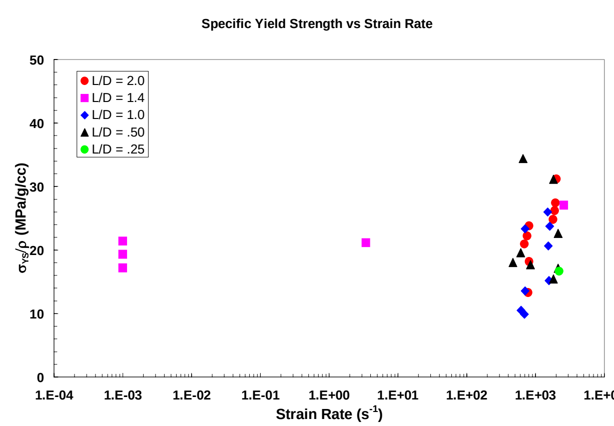

Figure 8. Normalized yield strength vs. strain rate plots for yield stress normalized by sample density. Each point represents a single test

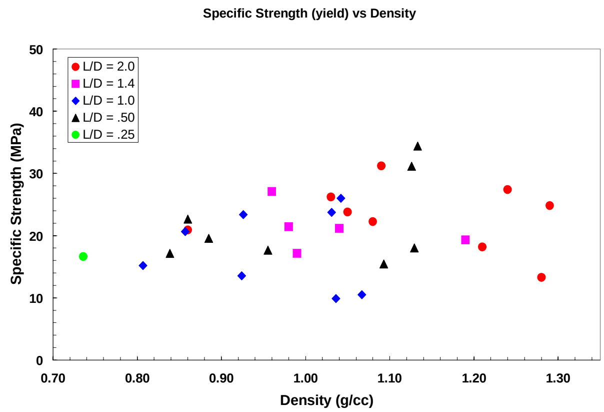

Figure 9. Normalized yield strength vs. density plots for yield stress normalized by sample density. Each point represents a single test

The reproducibility of the data is evident in the plots in Figure 10 for the 0/90 foam layup. Many of the high rate curves, including some not shown, are almost identical, including that for the 0/45/90/135 layup. A normalized flow stress at 10% strain versus strain rate is shown in Figure 11 showing slight strain rate dependence.

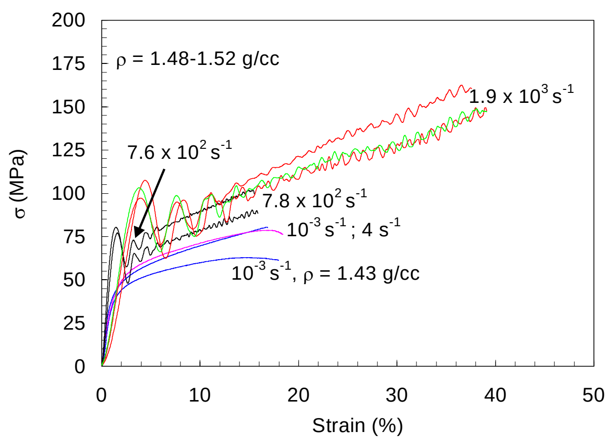

Figure 10. Engineering stress-strain curves for the 0/90 aluminum metallic foam samples

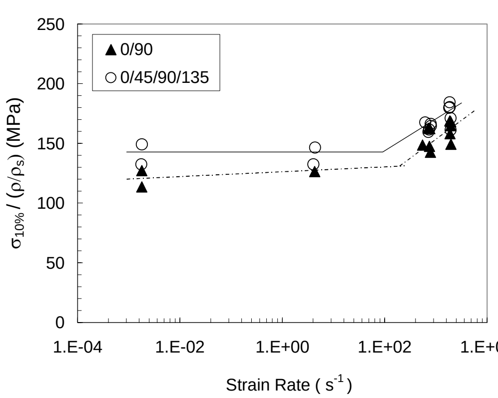

Figure 11. Normalized flow stress at 10% strain versus strain rate, showing slight strain rate dependence.

3.1 Component fabrication from CAD designs

The Al foam materials could be rapid prototyped into complex geometry directly from CAD designs. An example is shown in Figure 12. The green parts showed approximately 18-20% shrinkage on sintering.

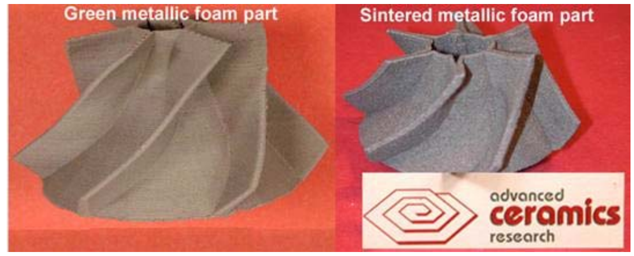

Figure 11. Turbine rotor fabricated from an Al foam. The sintered part is approximately 2" in diameter (right) and the green part (left) shows the degree of shrinkage.

4. DISCUSSION

The SHPB test results for the EFF foams were very consistent, especially given the 10% density variation for the range of samples tested. Post-test sample evaluation revealed some crushing of the voids within the walls/columns; the extent of void collapse is more severe at higher strains and strain rates. The surrounding solid provides continuous constraint until bending of the columns becomes unavoidable. The primary damage mechanism, however, is due to plastic flow of the highly-voided aluminum. Buckling and rupture of individual cell walls, characteristic of other metal foams was not observed. The EFF foams did not exhibit any localized flow or interactions.

The general shape of the compression stress-strain curves obtained differs from the typical three-stage curve, characteristic of other foams. The measured curves for the EFF foams show a more gradual elastic-plastic transition. The initial linear region of the curves corresponds to uniform deformation. However, the curves did not exhibit the characteristic plateau region (Gibson 1997), nor a marked densification region with sharply rising stress. In essence, the EFF material is a macroscopically open-cell, high-density foam, with "thick" pillar-like walls that neither buckle nor collapse. The closed cells in the walls/columns are basically widely distributed voids, and, therefore, do not significantly degrade the material strength via foam collapse mechanisms. More recent tests with the 0/90 and 0/45/90/135 layups, they exhibited a weak dependence of compression strength on strain rate, for strain rates less than 100 s^{-1}. Some strengthening is evident for the SHPB tests relative to the lower strain rate tests. The extent of the strain rate strengthening effect is particularly evident in the flow stress versus strain rate plot given in Figure 11.

Present work is focusing on the use of different metallic foam compositions using the EFF approach.

5. CONCLUSIONS

An extrusion freeform fabrication technique was employed to fabricate metallic foams with controlled pore size and orientation. Aluminum foams with different layups are possible by varying the deposition sequence. The compressive deformation behavior of this new type of aluminum foam was assessed under static and dynamic loading conditions. The aluminum foam investigated was processed using an extrusion freeform fabrication technique. The EFF process is a versatile rapid prototyping (RP) process that provides for the fabrication of near net-shape metallic foam components from highly loaded polymer binders filled with metallic powder. Metal foam parts are fabricated by the sequential deposition of multiple discrete raw material layers.

The foam contained approximately 50 to 60 % porosity. The dynamic compression response was evaluated in air using a split Hopkinson pressure bar (SHPB) system with aluminum bars, and strain rates ranging from 600 s^{-1} to 2000 s^{-1}. Compression tests were also conducted at lower strain rates (10^{-3} s^{-1} to 4 s^{-1}) to determine the extent of strain rate strengthening. The low strain rate tests were performed with a servo-controlled hydraulic test machine. The results were analyzed as a function of foam density, structure, and process conditions.

Compression test results indicate that EFF aluminum foams are stronger than aluminum foams processed by alternative methods; this is related to the higher density of the EFF foams and intrinsic structural differences. Strain rate strengthening was observed and is attributed to plastic flow of the EFF foam (i.e., void containing solid). The metallic foam layups exhibited a weak dependence of compression strength on strain rate, for strain rates less than 100 s^{-1}. Some strengthening is evident for the SHPB tests relative to the lower strain rate tests. The extent of the strain rate strengthening effect was particularly evident in the flow stress versus strain rate plot. Buckling and rupture of individual cell walls, characteristic of other metal foams was not observed. The EFF foams did not exhibit any localized flow or interactions.

The present work forms the groundwork for future work to create lightweight structures and honeycomb structures that can be used for fabricating components directly from CAD designs.

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