The Effect of Impact Velocity on the Deformation of Layered Metal Foam / Ceramic Composites

A.E. Markaki and T.W. Clyne

Department of Materials Science and Metallurgy, University of Cambridge,
Pembroke Street, Cambridge, CB2 3QZ, U.K.

Abstract

Static and low velocity instrumented impact tests were carried out on Al-12Si foam / Al_2O_3 laminates. Different support, specimen and indenter / impactor geometries were employed, yielding a two mode response of the laminate to loading. The first failure mode involved local crushing of the cross-section, and the second mode, flexural deformation. For both modes, laminates were found to exhibit similar responses and damage patterns when tested under static and dynamic loading. Energy absorption efficiency was significantly higher for the first mode. In this case, the extent of damage inflicted by static and impact testing was assessed and compared.

1. Introduction

Impact deformation induced in metal / ceramic laminates is an area of technical interest. A challenge is to maximise their energy absorbing capacity without impairing their low average density. A possible approach is the use of foamed metal layers. Most previous work concerns the impact response of lamellar composites containing polymer foam cores, while little has been done on metallic foam-core layered composites. Polymeric foams are usually employed when cost is of primary concern, but they tend to fail in a brittle fashion, with relatively little energy absorption.

When closed-cell metal foams are subjected to compressive loads greater than the collapse strength, deformation initiates via plastic bending and stretching of the cell walls[1]. This deformation results in large compressive strains. Studies[2-5] have revealed that, in principle, the energy absorption efficiency of metallic foams exhibits a weak strain rate-dependency. Increasing the applied strain rate tends to increase the deformation stress (plateau stress), but also limits the plateau strain. As a result, the net effect is in general a modest increase in the absorbed energy. The effect of impact velocity on the deformation of metallic foam / ceramic laminates has not previously been established.

The objective of this study is to investigate impact velocity effects during failure of layered metal foam / ceramic composites. The ceramic layers are used to spread the impact energy over a wide area, while the foam layeres have the potential for absorption of large amounts of energy. The system selected for investigation is an Al-12Si-0.6Mg (powder route) foam, which has been diffusion-bonded to Al_2O_3 in a layered arrangement.

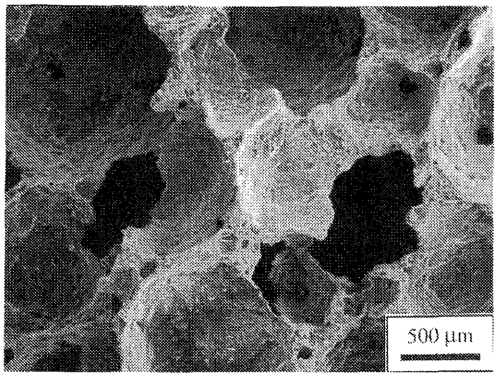
2. Experimental Procedure

2.1 Materials and Laminate Fabrication

Laminates consisting of alternate layers of Al_2O_3 and foamed Al-12Si-0.6Mg were prepared in a large vacuum hot press. Diffusion bonding was conducted in a high vacuum environment (~10^{-6} mbar) at 560°C for 5 hrs under an uniaxial pressure of 0.1 MPa. Aluminium spacers were used to prevent the foam from collapsing when heated. Two foam volume fractions, f_f (= $h_f / (h_f+h_c)$ where h is the layer thickness and the subscripts f and c refer to the foam and ceramic respectively), were used, while the Al_2O_3 layers were of constant thickness

(h_c=1 mm). Al_2O_3 layers were arranged as the outside layers.

The foam core material is made from an Al-12Si-0.6Mg alloy via a powder-based route[6]. In particular, Al alloy powder was mixed with TiH_2 powder, consolidated by extrusion and heated into the semisolid regime. As illustrated in Fig. 1, Al-12Si-0.6Mg foam is predominantly closed-cell, but there are a number of partially open cells. The porosity levels have been measured to be 73%, and the cell size distribution and average cell size are shown in Fig. 1. Important parameters for the powder-route foam are summarised in Table 1.



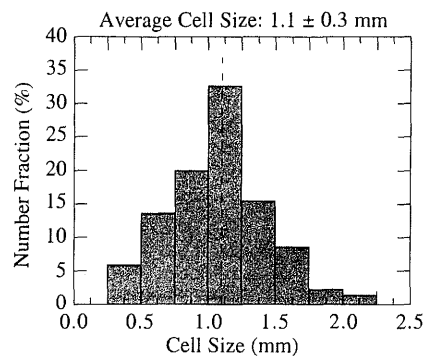


Fig. 1 SEM micrograph showing cell structure and cell size distribution for Al-12Si-0.6Mg foam.

Density	Porosity	Elastic Modulus	Compr. Strength (20% strain)	Tensile Strength	Flexural Strength
(Mg m^{-3})	(%)	(GPa)	(MPa)	(MPa)	(MPa)
0.72	73 ± 2	3.43 ± 0.3	7.10 ± 0.5	10.65 ± 0.4	9.67 ± 2.1

Table 1 Summary of the main properties of the Al-12Si-0.6Mg foam core used in the fabrication of layered structures.

2.2 Impact and Static Testing

Impact tests were carried out using the Rosand instrumented falling weight impactor at DERA Farnborough. Two specimen and support geometries were employed (Fig. 2): (a) Square specimens with a side length of 60 mm were firmly fixed between annular clamps of 40 and 60 mm internal and external diameter, respectively. (b) Rectangular specimens, of dimension 60 mm × 20 mm, were simply supported on the same annular ring.

The specimens were struck at their central point by an impactor of mass 2.63 kg. Spherical and cylindrical hardened steel tups, of 10 mm in diameter, were used for all tests (Fig. 2). Care was taken that the main tup mass is much greater than the tup tip mass, so that the dynamics of the impactor can be neglected. (If the main tup mass ratio is not close to unity, neglecting the impactor dynamics can lead to significant errors). After the first impact, the impactor was captured to avoid further damage due to rebound. During the impact tests, the drop height was varied to produce a range of incident impact energies. (The drop weight was kept constant). The impactor was instrumented with a strain-gauged 5 kN load cell, providing a record of force-time history. A time counter triggered by a pair of light gates was used to measure the tup velocity, just prior to impact. Impact load and duration were recorded by a data acquisition system which had an output sampling rate of 100 readings per millisecond. Moreover, in order to provide insight into the dynamics of the impact event, quasi-static tests were performed on a servo hydraulic testing machine. For continuity, the tests were conducted using the same specimen, support and indenter geometry, as employed in the low velocity impact tests. The indenter was fixed to the cross-head and the displacement rate was set at 1.2 mm/min.

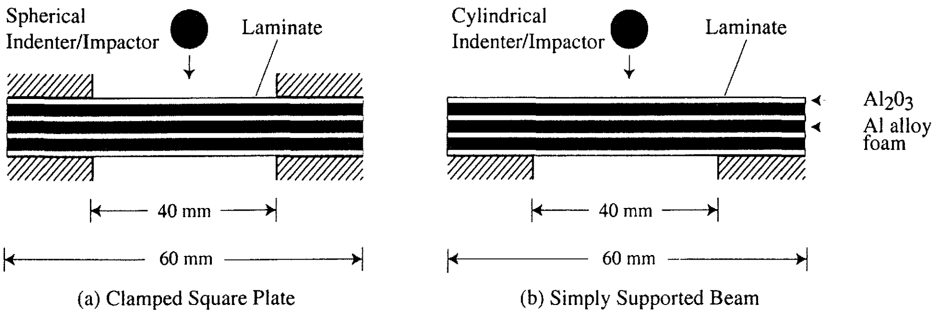


Fig. 2 Schematic of the set-up arrangement used during impact and static tests

Prior to and after impact, the nature and extent of damage was ultrasonically assessed using penetrant-enhanced X-ray radiography. X-ray radiography provided an overall area of damage as viewed from the top. Additionally, after the impact tests, sectioning of selected specimens was carried out and their cross-sections were visually inspected.

3. Results and Discussion

3.1 Clamped Loading

The laminates were tested at different impact energy levels producing increased damage up to penetration. The impact energy ranged from 2 J (1.23 m s^{-1} impact velocity) to 10 J (2.75 m s^{-1} impact velocity). At an impact energy of 2 J, the impactor penetrated the top facesheet (Al_2O_3), crushed the foam beneath and initiated damage in the next Al_2O_3 layer. At an impact energy of 5 J, the impactor entered to a depth of about half the thickness of the laminate. At both energies (2 and 5 J), the bottom face laminae suffered no damage. Furthermore, limited or no cracking was found to surround the vicinity of the impacted area of the top facesheet. In the region under the indenter, the foam was crushed, leaving a depression. At higher incident impact energies (10 J), laminate penetration occurred. Extensive local damage of the backface was observed as the impactor pushed out the broken material. The damage pattern in the backface was not symmetric and in some cases delamination crack fronts reached the laminate boundaries. As at low impact energies, indentation / penetration occurred with almost no evidence of out-of plane deformation of the top ceramic. Fig. 3 shows the damage inflicted on Al-12Si foam / Al_2O_3 laminates for two different levels of impact energy.

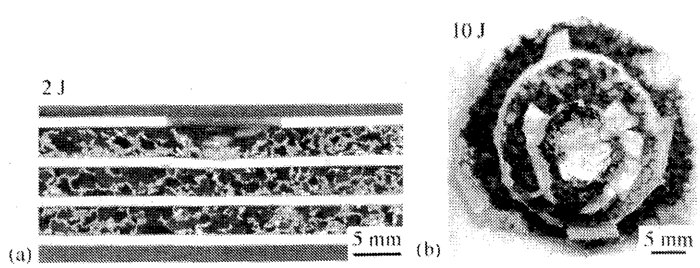


Fig. 3 (a)Diametric cross-section of partially-penetrated laminate (incident impact energy 2 J) and (b) the punched out disk after penetration (10 J). Local crushing of the foam layers has taken place

Fig. 4 shows typical load-displacement curves for penetrated Al-12Si foam / Al_2O_3 laminates, with foam layer thickness, h_f, of 2 and 3 mm under static and dynamic conditions. For both static and dynamic tests, the load increases with displacement of the indenter / impactor up to a first discernible failure point. At this point, the load drops and, after this, the load oscillates with progressive damage until the specimen rapidly loses its load carrying ability (continuous load decrease). Curves show that increasing the impact velocity from 2×10^{-5} m s^{-1} to 2.75 m s^{-1} has little effect on the load-displacement response. It was found that the energy required for penetration under impact conditions was similar to that in the static case. In particular, the penetration energy was found equal to 6.5 and 9 Joules for laminates with h_f equal to 2 and 3 mm, respectively.

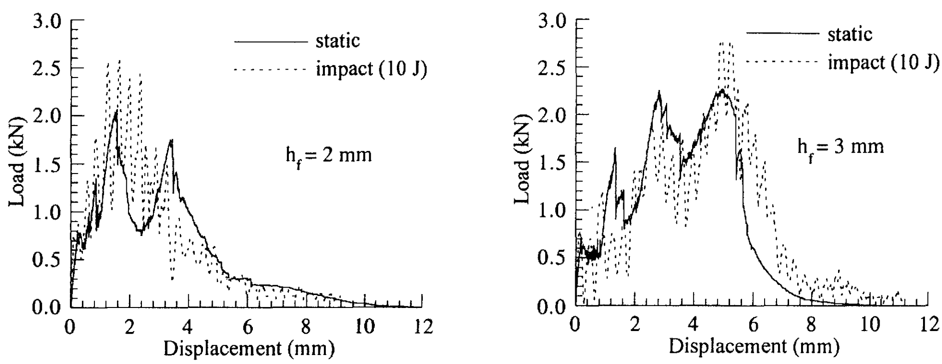


Fig. 4 Comparison between static and dynamic response for penetrated Al-12Si foam / Al_2O_3 laminates with foam layer thickness, h_f, of 2 and 3 mm

Overall, the damage mode of statically and dynamically loaded laminates involved indentation/penetration, surface and interlamina Al_2O_3 cracking, delamination and local crushing of the foam layers. Stereo pairs at +15°/-15° revealed that delamination occurred at different depths over the thickness of the laminate. The indentation size and the projected delamination area were measured with the aid of penetrant enhanced X-ray radiography. Fig. 5(a) shows the extent of the impact-induced damage for both static and dynamic loading. Note that although penetrated laminates exhibit similar failure modes and responses, overall the damage inflicted by static testing is less than that by impact testing.

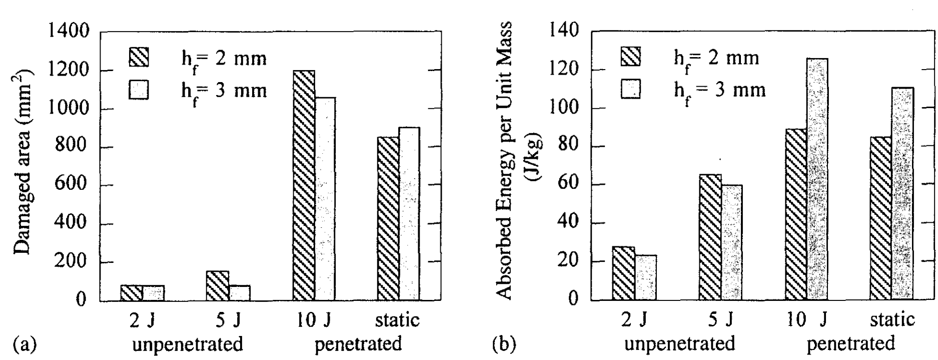


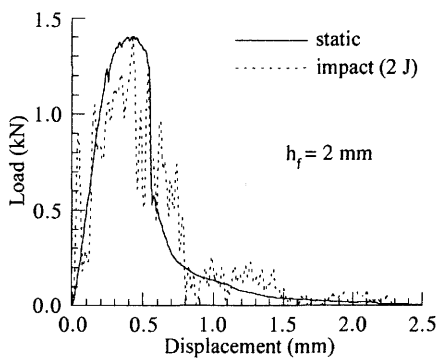
Fig. 5 (a) Damaged area and (b) specific energy absorption

To allow for more meaningful assessment of the energy absorption performance of the laminates, specific energy absorption values were calculated (Fig. 5(b)). For low impact energies (2 and 5 Joules), the specific energy absorption values were similar for both foam layer thicknesses. For higher impact energies (10 J), fully-penetrated laminates with thinner foam layers were found to absorb less energy, which is probably a consequence of the greater constraint on plastic deformation within the thinner layers.

3.2 Simply Supported Loading

The simply supported beam laminates were subjected to impact energies of 1 to 3 Joules corresponding to impact velocities up to 1.51 m s^{-1}. Fig. 6 shows typical load-displacement curves of simply supported bend laminates, with h_f of 2 mm, under static (2×10^{-5} m s^{-1}) and dynamic loading (1.23 m s^{-1}). For both the static and dynamic cases, the fracture energy was found about 0.9 J (for both h_f values). Energy absorption was thus appreciably lower than that for clamped loading. The reason for this difference can be attributed to the fact that, in clamped loading, compressive deformation of the cross-section takes place as the impactor / indenter pushes the broken material against the backface prior to penetration. Under simply supported loading, the specimen failed under flexural conditions[7].

Fig. 6 shows the side surface of an Al-12Si foam / Al_2O_3 beam laminate after impact. Beam laminates preferred a long path for failure. Damage developed in steps through successive layers forming a non-planar crack.



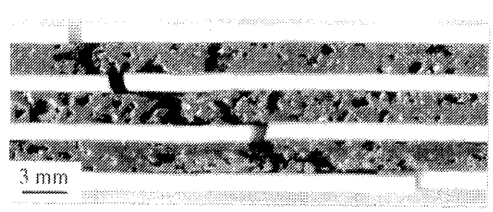


Fig. 6 Comparison between static and impact response for Al-12Si foam / Al_2O_3 beam laminates with foam layer thickness of 2 mm. Also shown, fracture through the thickness of impacted beam laminate (note that pores are smeared during cutting)

4. Conclusions

Static and low velocity impact tests were carried out on clamped and simply supported Al-12Si foam / Al_2O_3 laminates.

1. The energy required for dynamic penetration of the laminates was similar to that in the static case for both clamped and simply supported specimens. For both loading modes, laminates were found to exhibit similar load-displacement responses and damage patterns under static and dynamic conditions, suggesting that the impact velocity has little effect over this range.

2. For clamped loading, energy absorption efficiency was somewhat higher for penetrated laminates with thicker foam layers, presumably due to lower constraint on plastic deformation than in the laminates with thinner foam layers. Energy absorption levels of about 10 J (for a damaged region of mass ~20 g) were measured.

3. Energy absorption for simply supported beam laminates was considerably lower.

Acknowledgments

Thanks are due to the State Scholarships Foundation of Greece for financial support (AEM), to Dr F. Simancik (Slovak Academy of Sciences, Slovakia) for providing the metallic foam, to A. Foreman (DERA Farnborough, UK) for assistance with impact testing, and to R.J. Stearn and Dr T.J. Matthams (Cambridge University, UK) for useful discussions.

References

1. L. J. Gibson and M. F. Ashby, *Cellular Solids*, 2nd edn., Cambridge University Press, Cambridge, (1997).
2. M. Otsuka, N. Houjo, A. Kojima, M. Itoh and E. Ishii, *Mechanical Properties of Aluminum Foam*, Light Materials for Transportation Systems, Ed: N. J. Kim, (1993), pp. 435-444.
3. L. D. Kenny, *Mechanical Properties of Particle Stabilized Aluminum Foam*, Mater. Sci. Forum, 217-222 (1996), pp. 1883-1890.
4. J. Lankford, JR., and K. A. Dannemann, *Strain Rate Effects in Porous Materials,* Proc. Porous and Cellular Materials for Structural Applications, Eds: D. S. Schwartz, D. S. Shih, A. G. Evans and H. N. G. Wadley, Vol. 521, MRS, San Francisco, (1998), pp. 103-108.
5. V. S. Deshpande and N. A. Fleck, *High Strain Rate Compressive Behaviour of Aluminium Alloy Foams*, Int. J. Impact Engng, (1999), submitted.
6. F. Simancik, H. P. Degischer and H. Wörz, *Foamed Aluminium-Light Structural and Insulation Material*, Proc. 4th Europ. Conf. Advanced Materials & Processes (Euromat) (1995), Venice/Padua, Vol. IV: Structural Metallic Materials, Assoc. Italian. de Metall., pp. 191-196.
7. A. E. Markaki and T. W. Clyne, *Energy Absorption during Flexural Failure of Layered Metal Foam / Ceramic Composites*, Proc. 12th Int. Conf. Composite Materials (1999), Ed.: T. Massard, Paris, in press.