Applied Mechanics and Materials Vol. 82 (2011) pp 142-147
Online available since 2011/Jul/27 at www.scientific.net

doi:10.4028/www.scientific.net/AMM.82.142

Characterisation of aluminium matrix syntactic foams under static and dynamic loading

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Keywords: Aluminium matrix syntactic foam, energy absorption, compression test, drop weight and workbench.

Abstract. Development of a lightweight, strong and energy-absorbing material that has potential application for the protection of vehicles and occupants against impact and blast, is a difficult challenge facing the materials community. Aluminium matrix syntactic foams will be investigated as a possible core material as part of a multi-layered protection system for military vehicles. Aluminium matrix syntactic foams are composite materials consisting of an aluminium matrix implanted with hollow or porous ceramic particles. This paper investigates the mechanical properties of aluminium matrix syntactic foam with different sizes of ceramic micro-spheres and different grades of aluminium, fabricated by the pressure infiltration method. The static crushing behaviour of the foam was investigated under two test conditions using an Instron 4505 machine. Results are compared and discussed. The dynamic compressive response was investigated using a drop-weight impact test machine. It was found that the particle size of the ceramic micro-spheres and the grade of the aluminium metal have a significant effect on the energy absorption capacity of the material. The compressive strength of the syntactic foam was found to increase with increasing compressive strength of the metal matrix.

Introduction

Currently, the impact resistance of engineering structures, subjected to blast and impact loads, is of great interest in the engineering community and government agencies for providing protection against possible terrorist threats. Development of a light weight, strong and ductile material that has application to the protection of vehicles and occupants against impact and blast is a formidable challenge facing the materials community. In a blast or an impact, a structure usually undergoes large plastic deformation or break. The important characteristics of structural response include, (i) mode of deformation and failure, (ii) impulse transfer, and (iii) energy absorption in plastic deformation [1].

The deformation of metallic foams has been the subject of numerous studies, which have mainly focused on conventional open and closed cell metallic foams. Some studies [2,3] have shown excellent energy absorbing capabilities in aluminium matrix syntactic foam during quasi-static and dynamic tests. Dynamic compression testing showed a 10–30% increase in peak strength compared to the quasi-static results. The strain rate sensitivities of these foams are similar to those of aluminum matrix composite materials. These foams displayed excellent energy-absorbing capability, which suggests their potential use in high loading applications or for impact protection in situations where a high plateau stress is desired [4]. This paper investigates the mechanical properties of aluminium matrix syntactic foam fabricated by the pressure infiltration method. Static compression and three-point bending tests were performed as well as drop-weight impact tests. These are reported below.

Sample preparation

Aluminium matrix syntactic foams, corresponding to 25, 75 and 250 µm diameter ceramic spheres, were produced by pressure infiltration casting. The material contained ceramic micro-spheres representing ~66% of the matrix material weighing ~16 g and, aluminium material representing ~ 33% of the matrix material weighing ~45 g.

Sample Characterization

The static compression tests of the samples were carried out on a materials testing machine (Instron 4505) using a crosshead speed of 1 mm/min. From these tests, it was observed that the ceramic spheres first got rearranged and inter-spherical porosity got reduced. It was observed that above certain values of the load led to crushing of some spheres took place. The stress was found to increase steadily with increasing strain due to continued densification. All samples were manufactured under similar conditions with most of the samples showing onset of densification at a strain of 0.55. Cracks appeared at 45^{o} to the axial direction, indicating a shear type failure as shown in Fig. 1. Strong metal matrix had been reported to result in higher compressive strength of syntactic foams [5]. Also, the strength of syntactic foams had been found to depend on the strength of the ceramic particles. Ceramic spheres with higher wall thickness/radius ratio were reported to result in increased compressive strength of the syntactic foams [6].

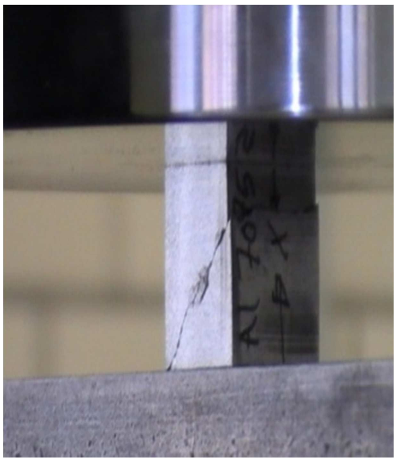

Figure 1: Shear failure during compression test

Quasi-static Compression test

The compression test has several intrinsic advantages in evaluating some basic mechanical properties of a material. It is relatively simple, requires only a small amount of material, and has simple sample presentation geometry (i.e.16.57mm by 8.12mm by 20.49mm). Several tests have been conducted with the samples of same sizes. The results of the experimental tests are shown in Fig. 2. These results have been used extensively for characterizing the modulus and strength of the material and for studying the strain hardening behaviour of the materials. The results show that Almuinium matrix syntactic foam with 75 micro spheres ceramics has the highest energy absorption capability. The results also showed that aluminium (6082) with 75 micro spheres ceramics has high yeild strength (135 MPa) and densification strain (0.35).

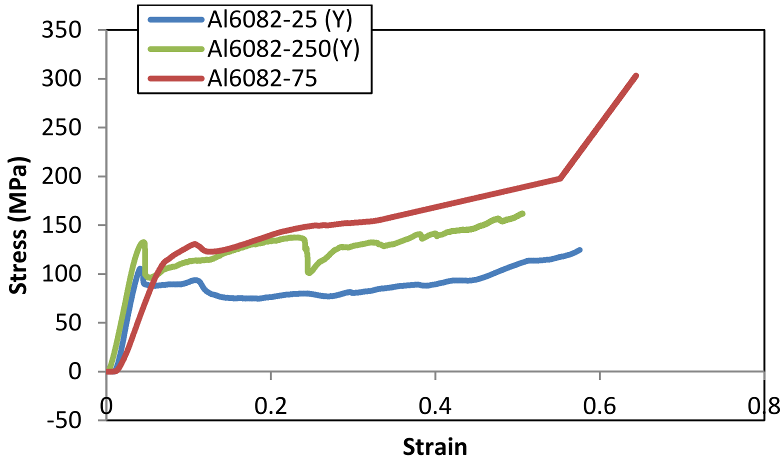

Figure 2: Compression test results of Al6082 with different micro-spheres ceramic

When aluminium grade was changed to 7075, the yield strength and densification strain were found increase. The results of the experimental and the modelling tests are shown in Fig. 3. The graphs show that the grade of aluminium and the size of micro-sphere ceramics both affect the energy absorption capability. Therefore, aluminium matrix syntactic foam (Al7075-75) has been chosen as the material of this study.

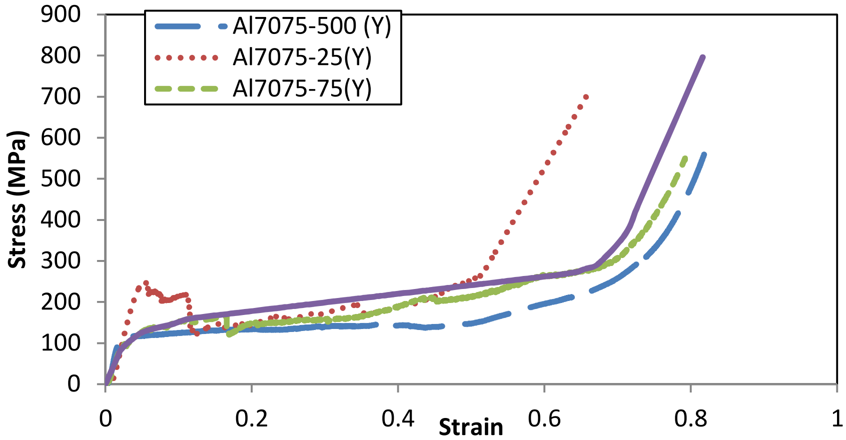

Figure 3: Compression test and modelling results of Al7075with different micro-sphere ceramics

Three-point bending test

The three-point bending flexural test provides values for the modulus of elasticity in bending E_f, flexural stress σ_f, flexural strain ε_f. The main advantage of a three-point flexural test is the ease of the specimen preparation and testing. The result of a three-point bending test on a sample of dimension, 10 mm by 10mm by 40 mm is shown in Fig. 4. The limitation of this method is that the test results are sensitive to specimen and loading geometry and strain rate. The stresses are non-uniform and vary with the variation in tension on one surface to compression on the other. It is also more open to variations in the choice of specimen geometry and details of the loading system, which can significantly affect the test results.

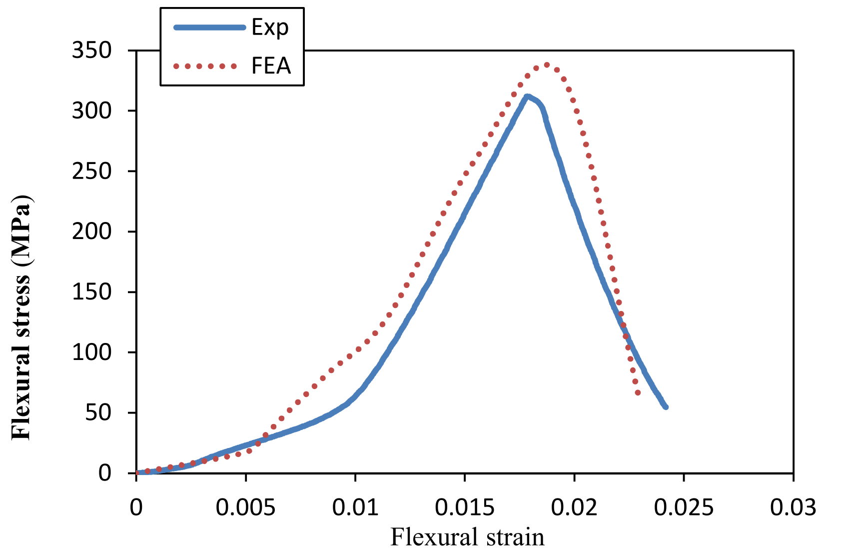

Figure 4: Three-point bending test and modelling results of Al7075-75 syntactic foam

Drop weight test

A drop weight impactor tower was used to impart a dynamic load and reproduce the failure modes and mechanism likely to occur. It consists of a heavy impactor, guided by two smooth steel rails, and is allowed to fall from a given height to strike the target. The incident energy of the impactor was determined from the drop weight and the contact velocity of the impactor. The impactor force was detected by using a load cell that is fixed above the indenter and recorded using a computer. The height of heavy impactor was fixed at 500mm; the load cell could record up to100 kN, the impactor velocity was varied by changing the release height of the carriage. The specimen geometry was set at approximately, 16.57 mm x 8.12mm x 20.49mm. A high-speed camera was used to measure the velocity and the displacement of the impactor. In this test, the load was fixed at 11 kg and the height was variable in steps of 500, 750 and 1000 mm and speed in steps of 3.2, 3.8 and 4.2 m/s. The stress-strain curve obtained is shown in Fig. 5.

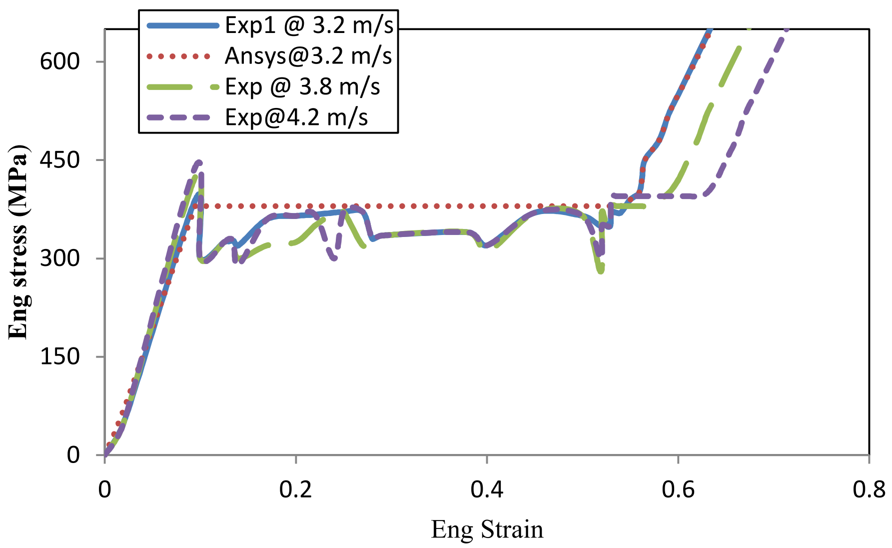

Figure 5: Comparison of drop weight test with the different speed loading and modelling in Autodyn

Numerical modelling

A software package, 'Ansys/ workbench static' was used for numerical analysis. A load of 100 kN was imparted to aluminium syntactic foam that had a dimension of 16.57mm x 8.12mm x 20.49mm. The sample was modelled using eight nodes hexahedral elements. Boundary condition was applied to the bottom of the sample that allowed the material to move freely in X and Z-directions while Y-direction was fixed. The sample material had been defined as multi-linear isotropic hardening model, while the drop weight test had been modelled by Ansys/ workbench dynamic. The kinetic energy of 11 Kg weight was imparted to the foam through its diameter of 60 mm when it is freely falling from a certain height. The initial velocity of the weight depended on the free fall height. Bi-linear material model and eight hexahedral elements were applied as the weight material.

In Ansys/ workbench, the material was defined by inputting its mechanical properties that had been found by the static compression test. To define a material in Ansys/workbench, physical properties, linear elastic and plasticity of the material must be defined. The material must have a valid density defined for explicit or implicit simulation. Isotropic elasticity was used to define linear elastic material behaviour by defining Young's modulus and Poisson's ratio. However, the plastic deformation was computed by reference to Von Mises yield criterion. The multi-linear isotropic model was used to define the yield stress (σ_y) as a piece-wise linear function of plastic strain, ε_p. The multi-linear isotropic model has been defined by introducing up to ten of stress-strain pairs.

Conclusions

Aluminium matrix syntactic foam has been characterised under static and dynamic loading. Compression and three-point bending tests have been conducted as a static approach and a drop-weight test as a dynamic approach. It has been found that the aluminium matrix syntactic foams have a higher energy absorption capability than metal foams. The specific energy absorption of aluminium matrix syntactic foam was found to be ~ 52 J/g when the weight was ~ 6.1g. This is comparable, within the present experimental error, to the value reported by Balch et al. [7] of 49 J/g for the same material. While Ashby et al. [8] achieved the specific energy value of 18 J/g for the metal foams. It has been shown that the compressive strength under dynamic loading is higher than the static loading by 10%-30%. In general, the simulation results have revealed good agreements with the experimental results. Future work will be focused on high dynamic loading tests like Split Hopkinson bar and blast loading to study the strain rate effect. The simulations will be refined by using the dynamic experimental data.

Acknowledgements

The authors would like to thank United Arab Emirates Government for sponsorship of this project, and also thank Mr. Steve Pennington, Mr. Dave Atkinson and Mr. Rafael Santiago for their support during the experimental work and Dr. L.P. Zhang for her assistance in preparing the syntactic foam samples, and Mrs Mariya Krates for her help.

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Performance, Protection and Strengthening of Structures under Extreme Loading
doi:10.4028/www.scientific.net/AMM.82

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