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Characterisation of Aluminium Matrix Syntactic Foams Dynamic Loading

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Abstract. It is a challenging task to develop a lightweight but also strong material with energy absorption capability to be used in vehicles to withstand impact and blast. This paper reports the research results on Aluminium syntactic foams as possible core materials for protection of military vehicles. In order to optimize their mechanical performance the characterisation of the foam behaviour at high strain rates and identification of the underlying mechanisms have been conducted. Mechanical tests were carried out on syntactic foams under high strain rate compression loading. The drop weight and split Hopkinson pressure bar (SHPB) techniques have been used to obtain data on the material behaviour under dynamic loading conditions. It was found that some samples show 30% higher plateau stress in the drop weight test than that of the quasi-static compression. In addition, it was found that the energy absorption of the aluminium matrix syntactic foam is higher than that of the ordinary aluminium foam. Experimental results from the above investigation are compared with the finite element predictions under the same loading conditions. Reasonably good correlation is obtained. The discussion on developing numerical modelling and the related validation are also given.

Introduction

Matrix syntactic foams are composite materials consisting of a matrix implanted with hollow or porous ceramic particles. Such foams are a relatively new class of material, which are manufactured using a variety of metal or polymer matrices and micro-sphere ceramics. It consists of micro-spheres ceramics, embedded in a metal matrix, such as aluminium, steel, titanium or magnesium. The ceramic micro-sphere could be porous or hollow structures, although hollow metal spheres are rarely used.

Metal matrix syntactic foams consist of a combination of ceramic micro-spheres and a metal matrix. Most metal matrices should be light metals such as aluminium, magnesium, titanium etc. The two types of micro-sphere in common use have either porous or hollow structures. Metal matrix syntactic foams can be fabricated by three different methods: infiltration, stir casting or powder metallurgy. Each processing method has advantages and limitations based on material system and composition [1].

Metal matrix syntactic foams are usually tested in compression under dynamic loading. Such loading can be carried out through, either low or high velocity impact. The dynamic loading is commonly applied by drop weight hammer and split pressure Hopkinson bar test. It was observed [2] that the dynamic stress-strain curve also has three regimes same as the quasi-static stress strain curve. The yield strength of metal matrix syntactic foams under dynamic loading is about 10-30% higher than that under quasi static compression. Moreover, Zhang and Zhao [3] investigated four samples of aluminium matrix syntactic foams under impact and reported that many oscillations appeared at the beginning of stress strain curve where the strain is low due to the high vertical vibration of the drop hammer. In addition, it was found that, out of four samples tested two had 10-30% higher plateau stress than that of quasi-static compression. Therefore, the plateau strength is mostly determined by the volume fraction of metal matrix in the metallic syntactic foam.

Cellular materials were tested under dynamic loading. Gold smith and Goldsmith [4] reported that, the honey comb material tested under dynamic loading showed that compared to static condition the mean crushing stress increases with the increase of dynamic loading rate.

The study of strain rate sensitivity of material is an essential subject in the scientific and technology community. Several of methods were experimentally used to determine the strain rate effect on the material properties.

The source of such ‘rate sensitivity’ of metal foam materials could not be clearly identified because of the difference of manufacturing process and the compositions of the foam [5]. Despand and Fleck [6] conducted dynamic tests by using split Hopkinson pressure bar (SHPB) on aluminium foam samples. The results did not reveal any rate sensitivity due to the small sample size. Moreover, Mukai, Danneman, Tan and Reid and Peng [7] reported that the rate sensitivity has an effect on the results of the mean stress that was obtained by using SPHB with respect to the static results.

Experimental work

Low velocity impact testing (Drop-weight). The dynamic properties of the (10x10x10 mm^3) foams were investigated by performing low velocity impact tests on the instrumented drop-weight tower, as shown in Figure. 1.

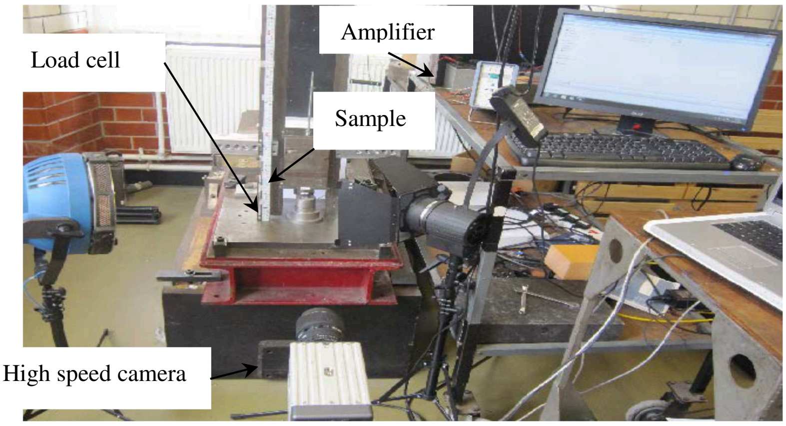

Fig. 1. The drop-weight test facility at the University of Liverpool.

In these tests, a carriage with a mass of 11.5 kg was guided by two vertical steel bars to impact the top of the sample. The sample was supported on a solid steel base. The impact velocity was varied by changing the release height of the carriage. The maximum height of the drop hammer was set to 1.5 m, which provides the maximum velocity of 5.42 m/s. In addition, the kinetic energy of the striker can be altered by varying the mass of the carriage between 0.4 kg and 35 kg.

A Kistler 9061 A piezo-electric load-cell was used to measure the force-time history. The maximum capacity of load-cell was 200 kN. The load-cell was located above the 25 mm diameter impact head. The impact force and signal were recorded using a Packard Bell computer with the Data Flow software package installed.

The impactor velocity and the deformation of the sample were measured using a high speed video camera (MotionPro-X4) located in front of the drop-weight tower. High resolution images were captured using a 50 mm lens. The Pro-Analyst software package was used to analyse the motion of striker during impact and the auto-tracking facility was used to obtain the displacement and velocity versus time curves.

Split Hopkinson pressure bar (SHPB)

The Split Hopkinson pressure bar test is widely used for the evaluation of high strain-rate effects on materials. The SHPB apparatus consists of two long slender bars, a striker, strain gauges, an output system and a specimen which is located between two rigid bars, as shown in Figure 2. As the striker bar impacts the end of the input bar, an elastic compression pulse is generated which travels through the input bar. At the input bar-sample interface, part of the pulse is transmitted to the output bar, while the remainder is reflected. The dynamic material properties can then be found from superposition of the incident and reflected pulses.

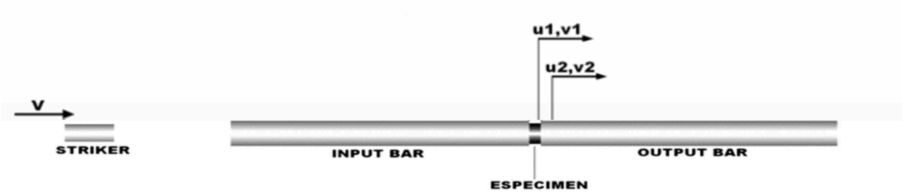

Fig. 2. Schematic of the test fixture for the SHPB test.

It was found that plastic deformation was caused by transmitted waves in the sample. Integration of the strain-rate in the specimen gives the strain on specimen. Therefore, the stress-strain properties can be determined when the pressure in the bars is within their elastic limit. The reflected and transmitted pulses therefore need to be identified. The stress in the specimen can be determined using following relation:

$$\sigma_s(t) = E\ \frac{A_o}{A}\varepsilon_T(t) \tag{1}$$

Also, the time dependent strain rate (t) and ε(t) are calculated using:

$$\varepsilon^{\cdot}(t) = \frac{2\ C_b\varepsilon_{r(t)}}{I_o} \tag{2}$$

$$\varepsilon(t) = \int_0^t \varepsilon^{\cdot}\ (t)dt \tag{3}$$

where $\sigma_s(t)$, E, A_o, A, C_b, εT (t), $\dot{\varepsilon}(t)$ and ε(t) are the stress in the specimen, the output elastic modulus of the pressure bar, the cross-sectional area of the output bar, the specimen cross-sectional area, the sound wave velocity in the bar, the transmitted strain, strain rate and strain, respectively.

Finite element modelling

Finite element analysis using commercial code Abaqus/Explicit was used to model the response of aluminium matrix syntactic foam under dynamic loads. Here, the low and high velocity impact loading were realised by setting up an initial velocity on the impactor.

An isotropic elastic-plastic constitutive model was used to model the aluminium matrix syntactic foam. The metal plasticity applied here can be either rate independent as in static or rate dependent models [8]. An isotropic, temperature independent model was used to model elastic response of the aluminium matrix syntactic foam. The uniaxial flow rate definition was used to define the rate dependent of the material as in equation 4.

$$e^{\cdot -pl} = h(q, e^{\cdot -pl}, \theta) \tag{4}$$

Where h, q and $e^{\cdot -\mathrm{pl}}$ are strain function, Von-Mises equivalent stress and the plastic strain equivalent, respectively. The rate dependent hardening can be expressed as

$$\bar{\sigma}\left(\overline{\varepsilon_{p\iota}}, \overline{\varepsilon^{\cdot}_{pi}}\right) = \sigma_y\left(\ \overline{\varepsilon_{p\iota}}\right)R(\overline{\varepsilon^{\cdot}_{pi}}) \tag{5}$$

where and R is the stress ratio = $\frac{\sigma^{-}}{\sigma_y}$. The ductile and shear damage criteria are used to model the damage of aluminium matrix syntactic foam. The ductile damage assumes that the equivalent plastic strain is a function of stress triaxiality and equivalent plastic strain rate at damage initiation.

An 8-node linear brick element, C3D8R, with reduced integration and hour glass control was used. Such the element usually provides a solution with high accuracy and low cost. The model assembly in the region of contact between the bars and the sample in SPHB model is shown in Figure. 3. The contact between input bar and the sample is constrained as in the experimental test while the interaction between the sample and the output bar is kinematic contact method.

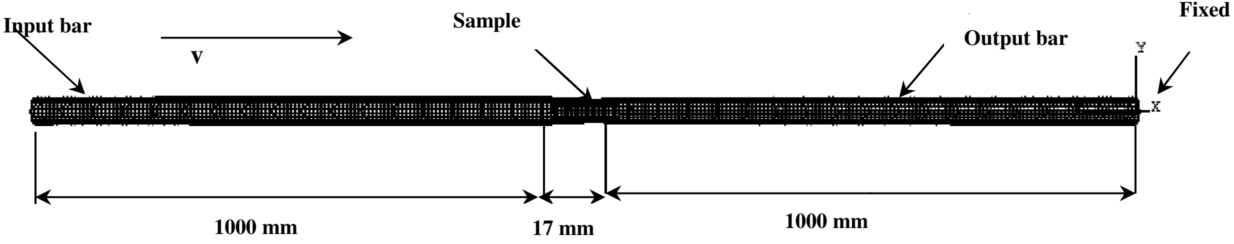

Fig.. 3. Detail of the model assembly at contact between the bars and the sample in split pressure Hopkinson bar model.

Results and discussion

Aluminium matrix syntactic foam has three types of failure mode during compression loading. It could failed as, compressive collapse due to the compressive stress on ceramic particles exceeds the compressive strength of the particles, shear failure due to the shear stress on a plane exceeds the shear strength of this plane, and tensile failure due to the tensile stresses at the cracks tip exceed the local tensile strength of aluminium matrix syntactic foam which cause the growth of cracks and failure of the material. The failure of metal matrix syntactic foam depends on the criterion is met first.

Fig.. 4 shows the engineering stress-strain curves from drop weight tests and FE simulation on aluminium matrix syntactic foams at different strain rates. As the loading velocity is increased, the yield strength, plateau stress and energy absorbed of aluminium syntactic foam increased. Also, it was observed that there are some oscillations in stress-strain curves during the drop weight test due to the vibrations on the drop weight carriage.

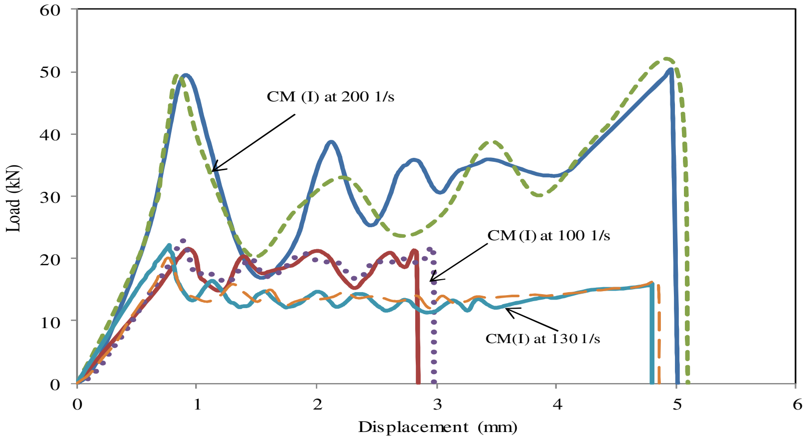

Fig..4 Stress-strain curves of aluminium matrix syntactic foam under drop- hammer loading at increasing strain rate (the solid line represents experimental results and the dashed line represents FE simulation).

The impact of striker the free end of input bar develops a longitudinal compressive incident wave in this bar. A part of this signal reflected back to the input bar while the remainder is transmitted through the sample to the output bar as shown in Fig. 5.

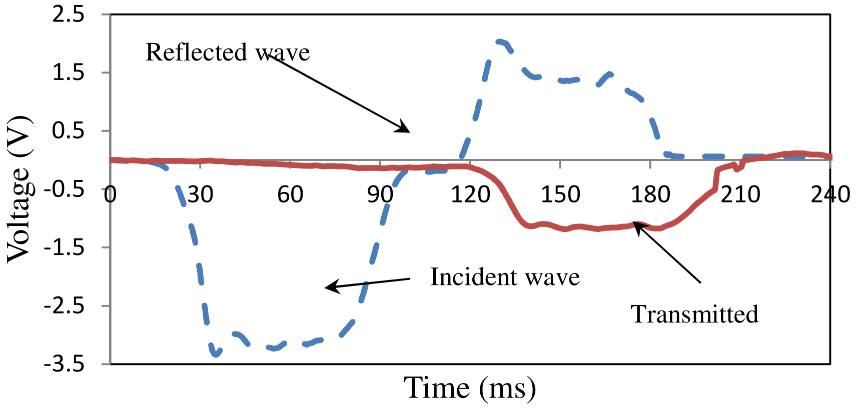

Fig..5 Incident, reflected and transmitted waves obtained from dynamic split pressure Hopkinson compression bars of aluminium syntactic foam

Fig..6 shows the stress-strain curves of the SPHB test on aluminium matrix syntactic foams at different strain rates. The analysis has revealed that the results obtained from numerical modelling agree reasonably well with the experimental results, which is shown in Figure. 4 and Fig. 6.

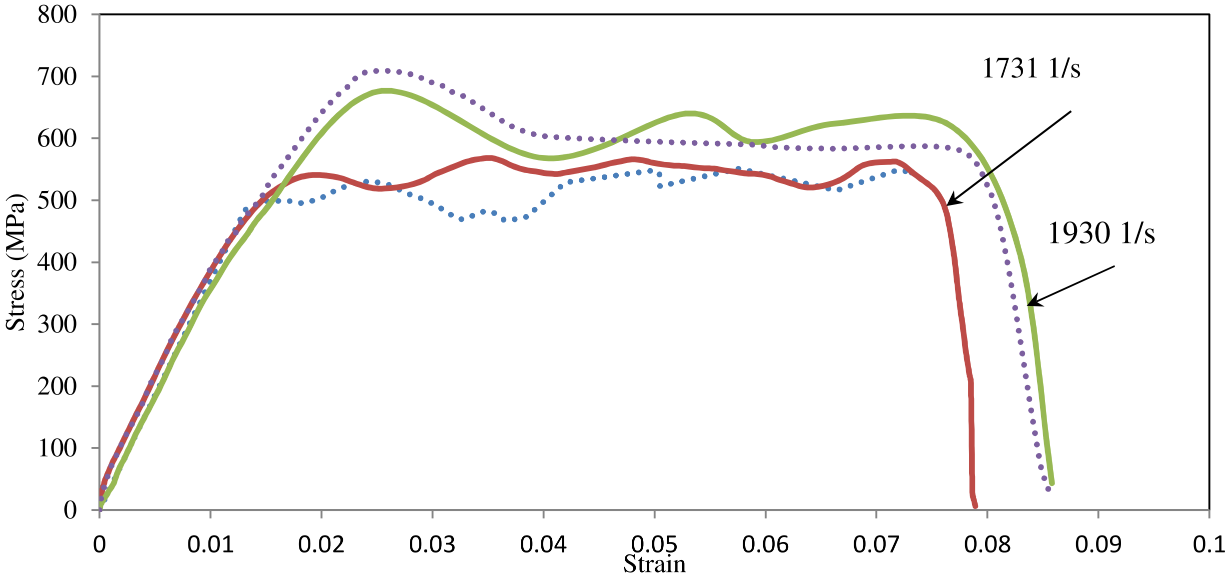

Fig. 6 Stress-strain curves of aluminium syntactic foam following compression tests on SPHB.

Conclusions

Aluminum matrix syntactic foam was characterized under low and high velocity loading. The experimental results have shown that the material is strain rate sensitive. The experimental results obtained have been used to validate the finite element simulations, in which very good correlation has been obtained. This indicates that the elastic-plastic foam model and the related failure criteria are capable of simulating structural response of aluminium matrix syntactic foams under both low and high dynamic loading. The models developed are ready to be used for further parametric studies to optimise structural behaviour of this type of foam.

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