Materials and Design 59 (2014) 296–302

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Characterisation of aluminium matrix syntactic foams under drop weight impact

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ARTICLE INFO

Article history:
Received 19 December 2013
Accepted 2 March 2014
Available online 12 March 2014

Keywords:
Metal matrix syntactic foam
Drop weight hammer
Strain rate
Finite element

ABSTRACT

It is a challenging task to develop a lightweight, and at the same time, strong material with high energy absorption for applications in military vehicles, which are able to withstand impact and blast with minimum injury to occupants. This paper presents a study on aluminium matrix syntactic foams as a possible core material for a protection system on military vehicles. Experimental work was first carried out which covers sample preparation through pressure infiltration and impact tests on aluminium matrix syntactic foams manufactured. Numerical models were then developed using commercial finite element code ABAQUS/Explicit to simulate the dynamic behaviour of the foam. The effect of strain rate on their compressive behaviour was investigated as these properties are vital in terms of the applications of these materials. Characterisation of the foam behaviour under low velocity impact loading and an identification of the underlying failure mechanisms were also carried out to evaluate the effective mechanical performance. It was found that samples subjected to drop weight impact offered a 20–30% higher plateau stresses than those of the samples subjected to quasi-static compression loading. The degree of correlation between the numerical simulations and the experimental results has been shown to be reasonably good.

1. Introduction

The impact resistance of engineering structures subjected to blast and impact loads is of great current interest within the engineering community. This is primarily due to the urgent need for providing protection against possible terrorist attacks. The development of lightweight, strong and ductile materials for use in the manufacture of military vehicles is a formidable challenge facing the materials community. When subjected to blast or impact loading, a structure usually undergoes large plastic deformation, possibly leading to partial or total failure. The important characteristics of such a structural response are: (i) the deformation mode and associated failure modes, (ii) the impulse and shock wave transfer, and (iii) the energy absorption through plastic deformations [1].

Metal matrix syntactic foams are a new class of composite material, consisting of a metal matrix with implanted micro-spherical hollow or porous ceramic particles. A metal matrix can be made of aluminium, steel, titanium or magnesium. Ceramic micro-spheres can be either porous or hollow spherical structures, and the size of the spheres determines the porosity and, to some extent, the strength of these materials. These kinds of material frequently offer a light weight and a high energy absorption capacity, and have been used in automotive, naval, aerospace and other industrial sectors. They can also be used to reduce shock loading effects such as those associated with mine blasts on military vehicles.

Cellular materials are characterized by several parameters, such as the constitutive law, the mean cell diameter, relative density (porosity), cell size and shape etc. Gibson and Ashby [2] analysed constituents of cellular solids structure by using X-ray tomography, optical microscopy and scanning electron microscopy. The porosity was measured by simply weighing samples with a known volume. Metal foams, fully impregnated with an opaque epoxy were polished and then characterized using optical microscopy. It was also reported that the scanning electron microscopy (SEM) is the most informative technology for the study of open cell foams, rather than for closed-cell foams. However, the X-ray tomography technique was found to be a better way to identify and investigate the deformation modes in cellular solids [3]. According to the study, large specimens were required to be cut into small pieces due to the low X-ray absorption on those samples. Another advantage offered by this technique is the facility to monitor deformations non-destructively.

An earlier study [4] has shown that the compressive strength of a metallic matrix syntactic foam is controlled by the strength of

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http://dx.doi.org/10.1016/j.matdes.2014.03.002
0261-3069/

metal matrix and the ceramic particles. Additionally, other parameters, such as the volume fraction, structure, distribution of the ceramic particles, etc., were found to influence the properties of the material [5,6]. For example, the compressive strength of a metallic syntactic foam decreases with increasing volume fraction of ceramic micro-spheres. It was reported that the compressive strength increases with increasing the size of ceramic micro-spheres [7,8]. It has also been predicted [9] that there should be a difference in the compressive strength for foams with different ceramic sphere sizes. Moreover, the thickness and the radius of the ceramic micro-spheres affect the compressive strength of the resulting metallic syntactic foam [10]. In contrast, the larger the size of ceramic micro-sphere is, the lower the strength of the ensuing metal matrix syntactic foam [11,12]. Palmer et al. [13] indicated that the lower compressive strength of a metallic syntactic foam is related to the large size of the micro-spheres. From this evidence, it is reasonable to conclude that the compressive strength of a metal matrix syntactic foam depends on three parameters: (i) the compressive strength of the metal matrix, (ii) the compressive strength of the ceramic micro-spheres, and (iii) the volume fraction of the metal matrix and ceramic micro-spheres. In addition, Orbulov and Májlinger gave a continuous mathematical description of response of metal matrix syntactic foams to compressive loading [14].

The compressive strength of the material is related to the energy absorption capability of foams and is usually quantified by using measurable stress–strain relationship. The ductile foam materials collapse through the crushing of ceramic micro-spheres, whereas the brittle ones fail due to shear [10]. Three other factors which affect the failure behaviour of metal matrix syntactic foams are [15,16]: (i) the structure of the ceramic micro-spheres, (ii) the volume fraction of the ceramic micro-spheres, and (iii) the volume fraction of the metal matrix.

Moreover, metal matrix syntactic foams were tested under dynamic compressive loading [16–18]. The impact of the falling weight caused no obvious damage to the specimens. Instead, the impactor rebounded with some residual energy [19]. It was observed that at high rates of strain, the aluminium matrix syntactic foams exhibit a higher plateau stress and peak relative to the values measured during a quasi-static test [16,20]. This indicates that the dynamic energy absorption capability of the aluminium foam is higher than the quasi-static value [21].

However, research on the dynamic response of aluminium matrix syntactic foams subjected to impact loading is limited, especially dynamic modelling. This paper presents experimental work on aluminium matrix syntactic foam samples prepared through pressure infiltration and subjected to impact. The samples produced are based on different volume fractions of aluminium matrix and ceramic particles, with the latter having various sizes. Here, the influence of strain rate on the peak stress, plateau stress, ultimate displacement and energy absorption is investigated. Following this, finite element models are developed to simulate the dynamic response of aluminium matrix syntactic foams subjected to drop-weight impact. This work covers three types of the foam subjected to impact loading at different strain rates. The numerical modelling output is then validated against the corresponding experimental results.

2. Experimental work

2.1. Fabrication of samples

Aluminium matrix syntactic foam can be fabricated by either stir casting or pressure infiltration. The effect of pressure infiltration on the microstructure and properties of the material was investigated in this study [22]. Here, the pressure infiltration casting process was used in which the metal matrix was placed above the ceramic spheres and pressed so that the molten aluminium infiltrated into the ceramic spheres where it solidified to produce a metal matrix syntactic foam. The infiltration casting process was conducted by hydraulic press, as shown in Fig. 1. This method has the advantage that the matrix and ceramic spheres are well bonded and the micro-spheres are usually uniformly distributed.

In the present work, aluminium matrix syntactic foams with ceramic spheres in the size ranges of 25–75 μm (CM(I)), 100–250 μm (CM(II)) and 250–500 μm (CM(III)) in diameter were produced by pressure infiltration casting. The matrix was based on aluminium alloy Al7075-T. The volume fraction of ceramic micro-spheres within the foam was 66% corresponding to a weight fraction of 88%. Fig. 2 shows a micrograph of the aluminium matrix syntactic foam, which indicates that some ceramic micro-spheres were fully infiltrated with molten aluminium.

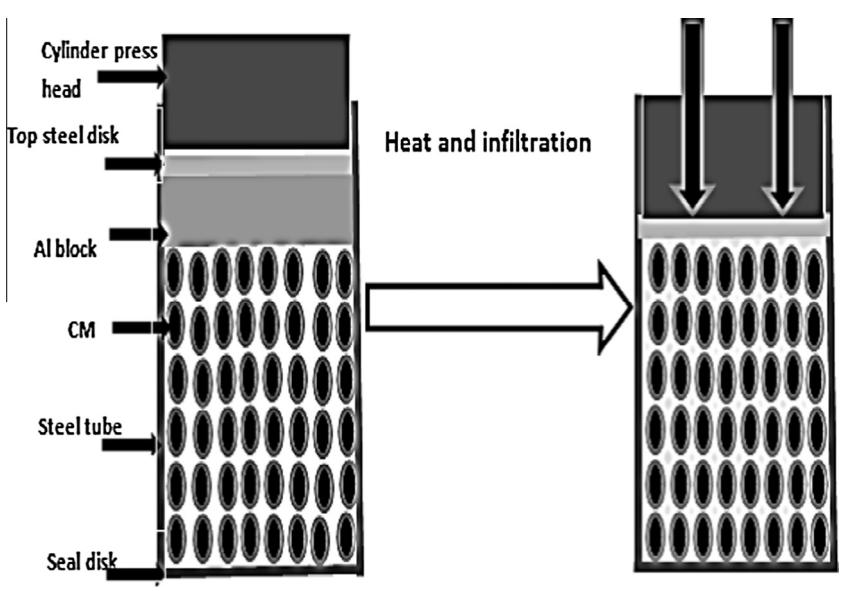

Fig. 1. Schematic of the preparation of metal syntactic foam by pressure infiltration.

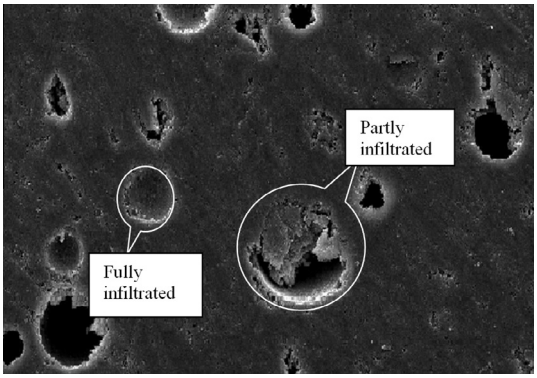

Fig. 2. Micrograph of aluminium syntactic foam which shows the region of some micro-spheres is partly infiltrated with aluminium.

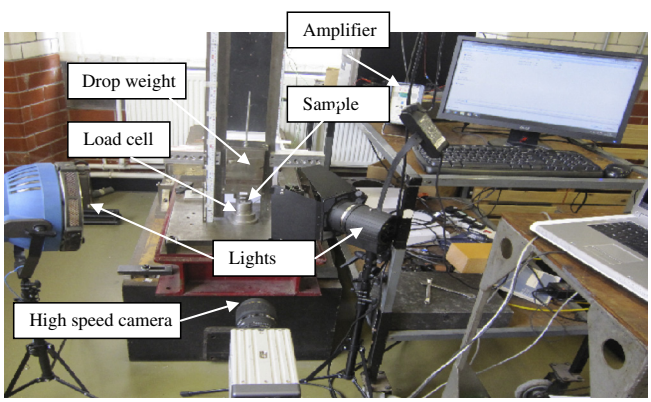

Fig. 3. The drop weight impact rig.

In the infiltration process, the interstices of ceramic microspheres are filled by molten aluminium through two flow routes, Route (1) where the molten aluminium fills the interstices through the interior of the ceramic microspheres, and Route (2) where the molten aluminium through the surface of the ceramic microsphere. The infiltration process is completed at the compact pad when the flow in Route (1) encounters a higher resistance than Route (2).

In contrast, when the flow in Route (2) has a higher resistance than Route (1), the completion infiltration process will be at the lower part of the ceramic microspheres.

2.2. Impact tests from drop weight hammer

The dynamic properties of the aluminium matrix syntactic foams ($10 \times 10 \times 10$ mm) were investigated by performing low velocity impact tests using a drop weight tower, Fig. 3. Drop-weight tests are useful for acquiring the dynamic properties of materials, such as energy absorption, fracture toughness, failure mechanisms, strength reduction and notch-sensitivity. [4]. Here, the test procedures were developed to suit aluminium matrix syntactic foams. Also, three repeat tests were undertaken in order to obtain repeatable results.

Here, a carriage weighing 12 kg is guided by two vertical steel bars to impact the top surface of the sample, which itself is supported on a cylindrical rig. The impact velocity was varied by changing the release height of the carriage. The maximum impact velocity that can be obtained is 6.5 m/s. The height used was increased up to 1.5 m, giving an impact velocity of up to 5.42 m/s and impact energies up to 176 J.

A Piezo-electric load cell (Kistler 9061) with the maximum capacity of 200 kN was used to measure the force–time history. The load cell was located above the 25 mm diameter impact head. The impact force signal was recorded by computer using the Data Flow Plus software package. The calibration factor for the load-cell was obtained by conducting a static calibration on an Instron machine.

Deformation of the sample was measured using a high speed 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 was used to detect the motion of the impactor during the impact event and auto-tracking was used to track the deformation and the velocity versus time curves [23].

The advantage of the drop-weight impact tests is that a wider range of sample geometries can be tested. However, stress wave reflection effects in the stress-time response of the specimen are often observed when using this method. Also, the limited values of strain-rate, which are dependent on the velocity of falling weight, represent a limitation [24].

Details of the samples used in the drop-weight impact tests are summarised in Table 1. Here, CM(I)1, CM(I)2 and CM(I)3 represent three samples belonging to the same type of the foam.

3. Finite element modelling

Here, the commercial finite element (FE) code ABAQUS/Explicit [25] was used to model the response of aluminium matrix syntactic foams under dynamic loads.

An isotropic elastic–plastic constitutive model was used to model the aluminium matrix syntactic foam. The metal plasticity applied can be either rate-independent (as in static), or rate dependent models [26]. The uniaxial flow rate definition was used to define the rate-dependent material, as expressed in Eq. (1).

$$\dot{\varepsilon}_{pl} = h(\bar{\sigma}, \bar{\varepsilon}_{pl}, \theta) \quad (1)$$

where h, $\bar{\sigma}$, $\bar{\varepsilon}_{pl}$ and θ are the strain-hardening function, the von-Mises equivalent stress, the equivalent plastic strain and the tem-

Table 1
Summary of the aluminium matrix syntactic foam samples used in the low velocity impact tests.

ID	Mass (g)	Depth (mm)	Width (mm)	Height (mm)	Initial velocity (m/s)	Relative density ρ/ρ_s	Strain rate (1/s)
CM(I)1	2.30	10.20	10.30	10.05	3.97	0.78	91
CM(I)2	2.32	10.30	10.25	10.10	4.40	0.77	120
CM(I)3	2.25	10.20	10.35	10.02	5.42	0.76	199
CM(II)1	2.35	10.25	10.20	10.05	3.97	0.79	96
CM(II)2	2.33	10.30	10.20	10.15	4.40	0.78	130
CM(II)3	2.45	10.30	10.25	10.10	5.42	0.82	202
CM(III)1	2.32	10.22	10.20	10.10	3.97	0.79	100
CM(III)2	2.38	10.25	10.20	10.15	4.40	0.81	136
CM(III)3	2.40	10.15	10.10	10.20	5.42	0.82	204

$\rho_s = 2800$ kg/m^3

perature, respectively. The rate-dependent hardening, in terms of the static relation, can be expressed as [26]:

$$\bar{\sigma}(\bar{\varepsilon}_{pl}, \dot{\bar{\varepsilon}}_{pl}) = \sigma_y(\bar{\varepsilon}_{pl}) R(\dot{\bar{\varepsilon}}_{pl}) \tag{2}$$

where $\dot{\bar{\varepsilon}}^{pl}$ and R are the equivalent plastic strain rate and the stress ratio, which are defined as:

$$\bar{\varepsilon}_{pl} = \int_0^t \sqrt{\frac{2}{3}\dot{\varepsilon}_{pl} : \dot{\varepsilon}_{pl}}\, dt \tag{3}$$

$$R = \frac{\bar{\sigma}}{\sigma_y} \tag{4}$$

The ductile and shear damage criteria were applied to model the damage in the aluminium matrix syntactic foam. The ductile damage criterion assumes that the equivalent plastic strain is a function of the stress triaxiality and the equivalent plastic strain at damage initiation, as expressed in the following equation:

$$\eta = \frac{-p}{\bar{\sigma}} \tag{5}$$

where p is the hydro-static pressure stress.

Shear damage is based on the assumption that the equivalent plastic strain is a function of the shear stress ratio and the equivalent plastic strain at the damage initiation, which is expressed as:

$$\gamma_s = \frac{\bar{\sigma} + k_s P}{\tau_{\max}} \tag{6}$$

where $\tau_{\max}$ is the maximum shear stress and k_s is the shear stress ratio.

The aluminium matrix syntactic foam samples were meshed using an 8-noded solid element (C3D8R), whereas the loading platens were modelled as rigid plates. Fig. 4 shows the mesh, boundary, geometric and loading conditions applied to the foam. The impact load was applied to the foam through a downward velocity at a reference point on the upper rigid plate. The corresponding reaction force was measured by the interaction between the lower surface of the top plate and the foam. Typical material properties of CM(I) used in the FE modelling are density = 2296 kg/m^3, Young's modulus = 3.72 GPa, Poisson's ratio = 0.29, with plastic strain hardening.

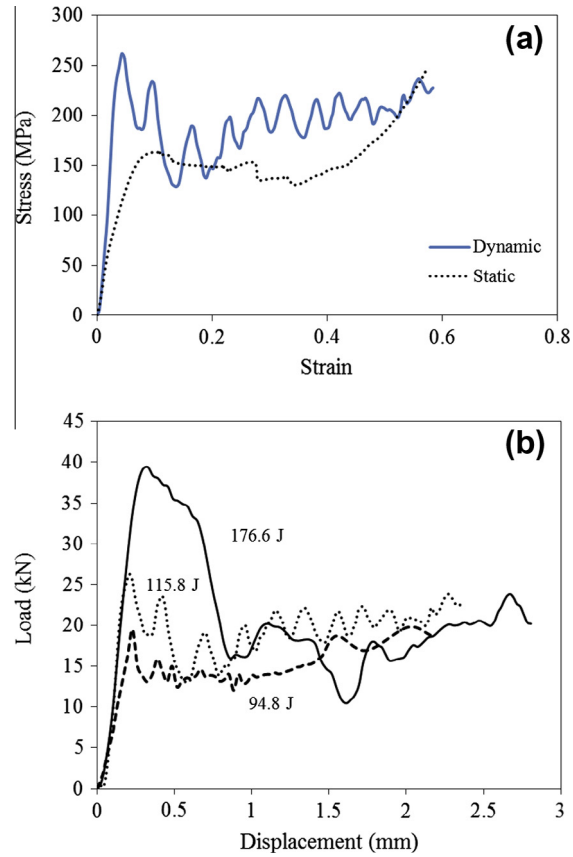

Fig. 5. Dynamic response of the aluminium syntactic foam CM(I): (a) drop-weight and quasi-static stress–strain curves, (b) low velocity impact load–displacement curves at different impact energies.

4. Results and discussion

The average densities of three types of syntactic foams (I, II, III) are calculated using the three sample densities of each type of foam. The density varies for each type of syntactic foam due to the difference in the size of the ceramic microspheres, the possibility of the difference of full infiltration, and the possibility of the difference in the number of voids between the ceramic microspheres. Usually, syntactic foam type (III) has a higher percentage of

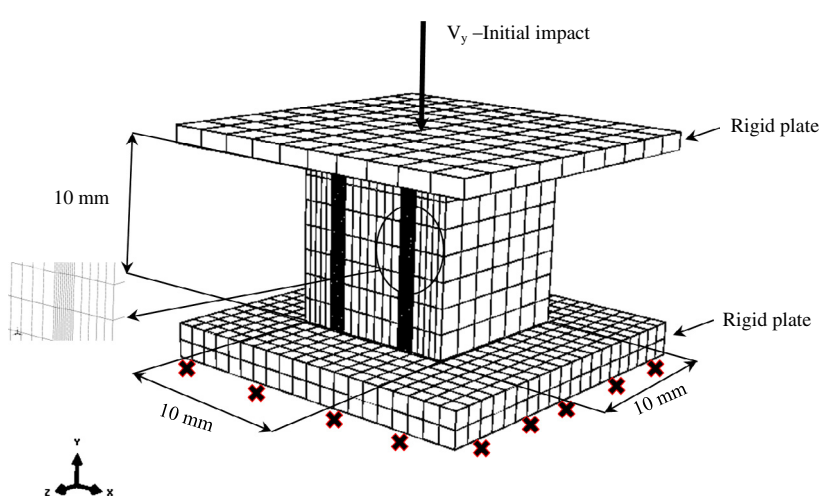

Fig. 4. Mesh, boundary and loading conditions in the finite element modelling of aluminium syntactic foam.

Table 2
Results of low velocity impact tests of the aluminium matrix syntactic foams CM(I), CM(II) and CM(III).

Foam ID	Peak strength (MPa)	Plateau strength (MPa)	Specific energy absorption (kJ/kg)	Impact energy (J)
CM(I)1	192.3	152.3	29.09	94.8
CM(I)2	202.3	189.4	42.50	115.8
CM(I)3	382.6	334.0	45.60	176.6
CM(II)1	213.3	191.2	31.90	94.8
CM(II)2	280.7	276.0	43.85	115.8
CM(II)3	502.0	338.8	48.04	176.6
CM(III)1	215.8	206.2	33.40	94.8
CM(III)2	327.1	267.8	47.40	115.8
CM(III)3	560.8	347.1	55.30	176.6

infiltrated ceramic microspheres and a lower number of voids between ceramic microspheres. In most cases, the densities of the aluminium matrix syntactic foams fall within a narrow range of 2156–2259 kg/m^3.

The infiltration pressure was set between 4 and 6 MPa. The higher infiltration pressure ensured that the ceramic microspheres pores were infiltrated. It was found that a lower infiltration pressure reduces the number of broken ceramic micro-spheres, however a small number of CM particles were found to be infiltrated with aluminium. This indicates that the molten aluminium infiltrated into the ceramic microspheres through the cracks that were existing before pressure infiltration. The higher infiltration pressure, the higher are the compressive strength and Young's modulus values due to the increase in the density of the foam.

A typical stress–strain trace for the aluminium matrix syntactic foam subjected to drop-weight impact, together with a sample subjected to quasi-static loading, are shown in Fig. 5(a). The results indicate that the peak impact stress is significantly higher than the corresponding quasi-static value. The impact response of the aluminium matrix syntactic foams is characterised by the initial peak stress followed by a sudden drop and some oscillations in the stress–strain trace, which has also been reported by other researchers [27]. Moreover, in the dynamic loading case, there is a clear failure in all three samples, whilst in the quasi-static case there is a sharp increase in the compressive stress following the onset of densification.

The results from low velocity impact tests on the syntactic foams are listed in Table 2. Fig. 5(b) shows the drop-weight load–displacement curves for the aluminium matrix syntactic foam CM(I) subjected various impact energies. All three curves exhibit a similar response, with the load increasing to a maximum followed by a subsequent drop due to cracking in the ceramic micro-spheres, then load then fluctuates around a plateau value [28–31]. The load–displacement traces may be divided into two regions: a linear elastic region and an oscillating plateau region. The impact peak load, which is the maximum force before the onset of plastic deformation, is found to increase with increasing impact energy. The peak load appears to be more sensitive to higher impact energies (a higher impact velocity for a given projectile mass). When the impact velocity is increased from 3.97 m/s to 4.40 m/s (corresponding to impact energies from 94.8 J to 115.8 J), the average maximum force for the three foams is increased by 35%. When the impact velocity is increased from 4.40 m/s to 5.42 m/s (corresponding to an increase in impact energy from 115.8 J to 176.6 J), the average maximum force increased by 36%.

It has been observed that the specific energy absorption capability of the aluminium matrix syntactic foams increases with increasing impact energy. The ability of the aluminium syntactic foams to absorb impact energy can be determined by calculating the area under the load–displacement trace. Clearly, with increasing, the initial stiffness of load–displacement trace increases, reflecting a significant strain-rate dependent behaviour in the three types of the aluminium matrix syntactic foam.

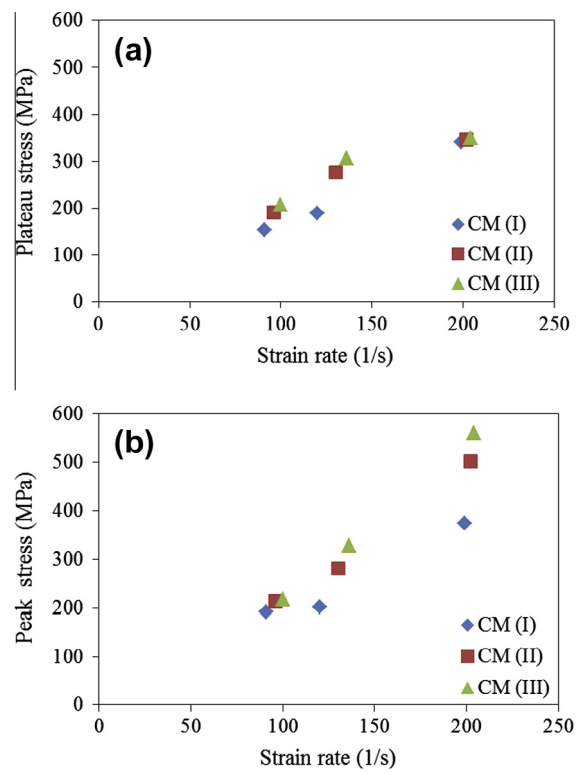

Fig. 6. Plot of peak and plateau stresses vs. strain rate for the aluminium syntactic foams CM(I), CM(II) and CM(III), (a) plateau stress, (b) peak stress.

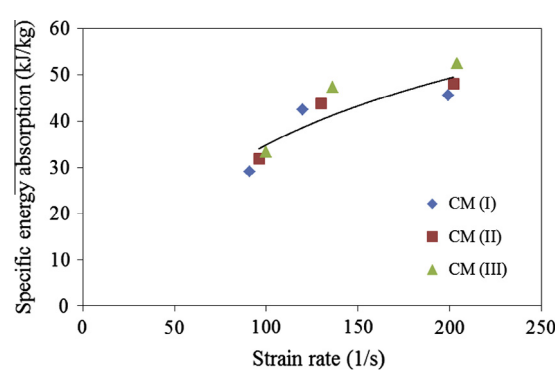

Fig. 7. Plots of the impact energy absorbed by the aluminium syntactic foams CM(I), CM(II) and CM(III) under loading with different strain rates.

Fig. 6 shows that the peak and plateau stresses values increase with strain-rate. The higher maximum stress under low velocity impact loading is associated with micro-inertial hardening of the rapidly displaced micro-sphere cell walls within and ahead of the localized deformation band. The effect of the inertia becomes evident, and the resistance of ceramic micro-spheres to collapse is

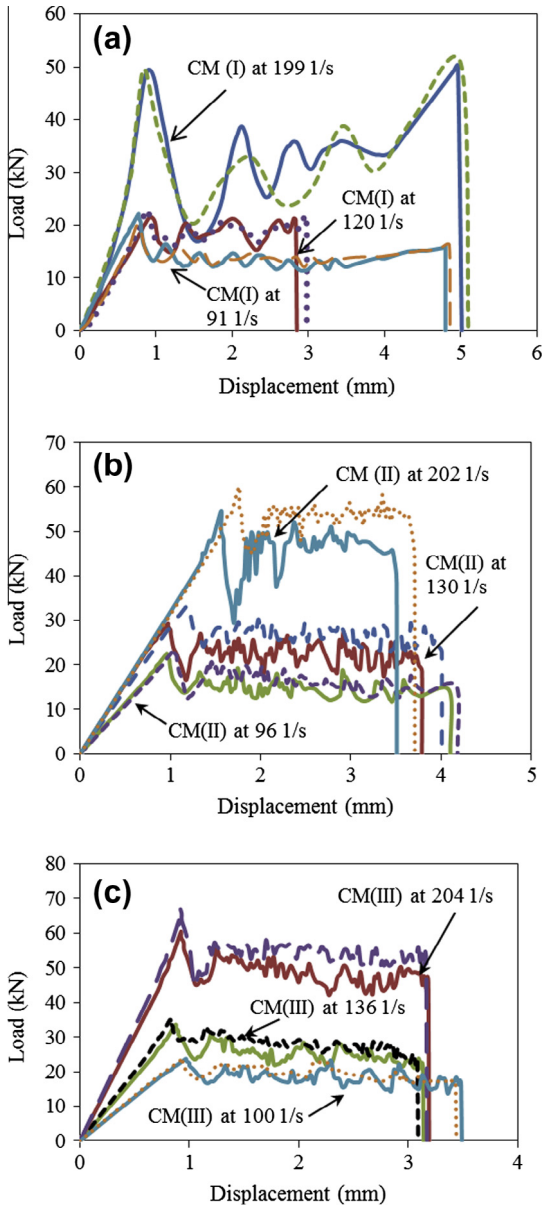

Fig. 8. Load–displacement traces of aluminium matrix syntactic foam under dynamic loading at different strain rate: (a) Al 7075-T with 25–75 μm ceramic micro-sphere, (b) Al 7075-T with 125–250 μm ceramic micro-sphere, and (c) Al 7075-T with 250–500 μm ceramic micro-sphere (the solid line represents experimental results and the dashed line represents FE simulation).

increased with strain-rate, which leads to an increased peak stress. Here, the results obtained in this study show the similar trend with the output from Rohatgi el al. [5], Balch et al. [8], Tao [9] and Rohatgi et al. [15]. For example, the peak stresses of the CM(I) type foam at strain-rates of 100, 133 and 200 1/s are 192, 202 and 383 MPa, which are 5.8%, 1.2% and 0.9% higher than the previous study results [9]. The higher peak stress values are due to the slightly higher strength of the aluminium matrix and ceramic micro-spheres.

The specific energy absorption capacity of the foams also increases with increasing strain rate, as shown in Fig. 7. For example, the specific energy absorption for the CM(III)3 foam is 55.3 kJ/kg when the strain rate is 204 1/s, while the specific energy absorption is only 33.4 kJ/kg at a strain rate of 100 1/s. The increase in energy absorption is related to the high plateau stress and densification strain. Clearly, the results shown in Fig. 7 indicate that the sample loaded at a strain rate of 204 1/s has a higher plateau stress and densification strain. Consequently, the foam has a capability to absorb higher levels of energy than those with a lower plateau stress and densification strain, which is similar to the existing results on aluminium foams [27]. Also, the output here for the CM(III) foam gives the similar trend to the previous results [9], i.e. the specific energy absorptions at strain-rates of 100, 133 and 204 1/s are 33.4, 47.4 and 55.3 kJ/kg, which are 1.4%, 5.0% and 4.4% higher than Tao's results [9].

The relative mechanical properties are calculated by dividing the yield strength and elastic modulus of the aluminium syntactic foam by the corresponding properties of the solid aluminium 7075-T (E_S = 94.4 GPa, σ_S = 646 MPa) under the similar impact loading. These results yield a direct comparison of the performance of the aluminium syntactic foams and the base aluminium. In general, the higher the density of the foam, the higher mechanical property ratios.

Fig. 8 shows the predicted load–displacement traces for the three types of aluminium matrix syntactic foam subjected to different strain-rates (drop heights). For comparison, the corresponding experimental results are also shown in the figure. It is clear that good agreement is obtained between the simulations and the experimental results. The results show that the size of ceramic particles has an effect on the strength of the foam. The results indicate that the best combination of Al7075-T with 250–500 μm ceramic microspheres, i.e. CM(III), has the highest strength among the composite combinations studied.

The foam CM(III)3 sample is compared with the associated simulation in Fig. 9. It is clear that basic features, such as the significant level of densification as well as the edge and corner configurations, are captured by the finite element model. This evidence, together with the accurately-predicted load–displacement

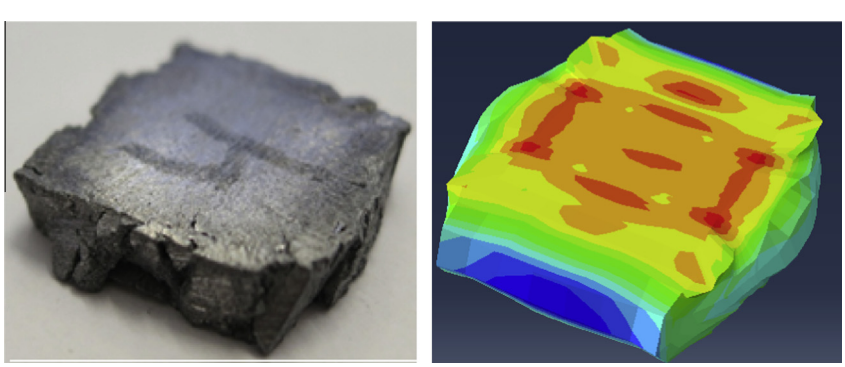

Fig. 9. Comparison of the tested foam (Al 7075-T with 250–500 μm ceramic microspheres at strain rate of 204 1/s) with the simulated foam.

traces, suggested that the finite element models can be used for further parametric studies to assist designing this type of the foam.

5. Conclusions

A series of drop-weight impact tests have been undertaken to investigate the dynamic response of aluminium matrix syntactic foams subjected to various impact loads. Here, foams with different proportions of aluminium matrix and ceramic particles, with various sizes, have been manufactured using an infiltration technique. The influence of strain-rate on the peak stress, plateau stress, ultimate displacement and energy absorption of the foam has been investigated. Finite element models have also been developed to simulate the response of such foams when subjected to equivalent dynamic loading.

It has been found that samples subjected to drop-weigh impact exhibit 20–30% higher plateau stresses than samples subjected to the equivalent quasi-static compression. Also, the specific energy absorption capacity of the foams increases with increasing strain rate, e.g. such increase for the CM(III)3 foam is 66% when the strain rate is increased from 100 1/s to 204 1/s. The results indicate that the best combination of Al7075-T with 250–500 μm ceramic microspheres, i.e. CM(III), has the highest strength among the composite combinations studied. The experimental results obtained have been used to validate the finite element simulations, in which very good agreement has been obtained. The FE models developed can be used to undertake more detailed parametric studies to optimise structural behaviour of this type of foam.

Acknowledgements

The authors would like to thank the Government of the United Arab Emirates for its sponsorship of this project. Also, thanks go to Mr. Steve Pennington, Mr. Dave Atkinson, Mr. M. Ruzaimi and Dr. M. Hassan for their support during the experimental work and Dr. L.P. Zhang for her assistance in preparing the syntactic foam samples, and Mr. Matar Al Humairi and Mrs. Mariya Krates for their encouragement.

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