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Plate-impact loading of cellular structures formed by selective laser melting

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Abstract
Porous materials are of great interest because of improved energy absorption over their solid counterparts. Their properties, however, have been difficult to optimize. Additive manufacturing has emerged as a potential technique to closely define the structure and properties of porous components, i.e. density, strut width and pore size; however, the behaviour of these materials at very high impact energies remains largely unexplored. We describe an initial study of the dynamic compression response of lattice materials fabricated through additive manufacturing. Lattices consisting of an array of intersecting stainless steel rods were fabricated into discs using selective laser melting. The resulting discs were impacted against solid stainless steel targets at velocities ranging from 300 to 700 m s⁻¹ using a gas gun. Continuum CTH simulations were performed to identify key features in the measured wave profiles, while 3D simulations, in which the individual cells were modelled, revealed details of microscale deformation during collapse of the lattice structure. The validated computer models have been used to provide an understanding of the deformation processes in the cellular samples. The study supports the optimization of cellular structures for application as energy absorbers.

Keywords: cellular structures, selective laser melting, shock, impact

(Some figures may appear in colour only in the online journal)
1. Introduction

Metallic cellular materials have been investigated recently for blast mitigation applications, for example, as the cores of light-weight metallic sandwich structures. The combination of material choice and cellular core architecture can be used to enhance sandwich performance, improving bending stiffness and strength at reduced weight, dissipating energy in core compression and exploiting fluid–structure interaction effects to reduce momentum transfer to the structure [1, 2]. Metallic cellular cores that have been investigated for this purpose include metallic foams [3–5], periodic arrays of bars such as the pyramidal and tetrahedral lattices [6, 7] and prismatic cores such as the square honeycomb and corrugated cores [8, 9]. The dynamic compressive response of the cellular cores, which are typically of centimetre scales, plays an important role in these applications. It has been shown that at high impact velocities porous materials tend to deform by the propagation of compaction waves. Reid and Peng performed experiments in which wood samples were impacted under uniaxial strain conditions at velocities ranging up to 300 m s$^{-1}$ [10]. One-dimensional shock theory was used to explain the observations. This work has since been extended to include porous aluminium targets and the model has been refined to incorporate more representative crushing models [11–13]. Finite element simulations of periodic planar lattices including hexagonal, rhombus, square, triangular and Kagome lattices uniaxially compressed at velocities up to 140 m s$^{-1}$ have been conducted by Qui et al [14]. These studies have revealed the modes of dynamic compressive collapse of cellular materials at impact velocities approaching the plastic wave speed in the material [15, 16]. However, experimental investigation at higher compression velocities (e.g. above 300 m s$^{-1}$), as might be encountered in severe blast scenarios, poses particular practical challenges.

An approach that has excellent potential to advance the technology of energy absorbing cellular materials, particularly at higher loading energies, is to use additive manufacture. This is a relatively novel technique which enables complex three-dimensional structures to be fabricated. One variant, known as selective laser melting (SLM) has been used by several investigators to generate a range of structures. In the SLM technique, a laser is sequentially rastered over a bed of metal powder, following a path defined by an electronic model file. The powder experiences local surface melting and welding, resulting in features on the scale of hundreds of micrometres, with the limiting factor being the size of the region of powder which is melted by the laser. Mines [17] and Smith et al [18] have used SLM to form body-centred-cubic structures. Wang et al [19] have studied a structure designated Kagome which has a three-fold axis of symmetry and McKown et al [20] have studied an octahedral lattice.

The geometric control afforded by SLM can be used to directly study the relationships between cellular meso-structure, micro-mechanical response and energy absorption. It is straightforward with SLM to fabricate lattice materials with a wide range of different cellular architectures. In contrast to many of the techniques currently in use to manufacture large-scale structures, the technique could readily be used to tailor structures to provide optimum protection against specific threats. In addition, structures can be manufactured with cell sizes down to the millimetre range with internal feature sizes down to $\sim$100 $\mu$m. This capability is attractive in scenarios in which miniature components need to be protected against blast and impact. Another plus point is that millimetre scale cellular structures allow the compressive collapse of potential energy absorbing materials to be evaluated over a wide range of impact velocities using a gun-driven plate-impact configuration. As will be shown later in this paper, the plate-impact configuration can be used to generate data under uniaxial strain conditions. This load configuration can be analysed using one-dimensional shock theory as in much of the past work on compression of porous materials [10–14]. Further, as will be
shown later, the experiments are amenable to comparison with relatively low-cost computer simulations.

Although, in principle, the relative merits of alternative cellular configurations can be assessed by computer simulation, a vital prerequisite of such simulations is to determine the validity of the chosen code in the relevant regimes of loading and, for the submillimetre structures considered in this work, length-scale. The 2D/3D multi-material Eulerian hydrocode CTH [21], developed at Sandia National Laboratories, is ideal for such an iterative study, since it includes the ability to construct part geometries from external CAD files. As rapid prototyping technologies widely use CAD, it becomes straightforward to directly import structures into CTH, thereby allowing 3D simulations to be run without the need to recreate the structure in the hydrocode. In the work described in this paper, the results of plate-impact experiments on a trial stainless steel cellular structure, of an appropriate scale to be investigated with standard plate-impact techniques, are compared with 2D continuum CTH simulations run using the $P(\alpha)$ model and with full 3D simulations. The principal objectives of the work described in this paper are to report experiments in which a convenient cellular structure is uniaxially compressed at velocities extending upwards from most previous work, and to show that the CTH has the capability to reproduce the experimental data, thereby giving confidence in the use of CTH as a predictive tool. We believe the results will contribute to a number of study areas including the optimization of cellular structures for energy absorption, the shock compaction of granular materials and the generation of hot spots in shocked heterogeneous explosives.

2. Material description

A graphical depiction of the lattice structure which forms the basis of this study, (for convenience designated the ‘MS1’ structure, after Mark Swan, the engineer who created the file), is shown in figure 1. The structure created using CAD software consists of an array of 316L stainless steel vertical columns of diameter 0.4 mm separated in a square array by 1 mm; the column structure is intersected by rods angled at 45° as shown. The SLM process used particles of diameter $\sim$20–40 $\mu$m in layers of thickness $\sim$40 $\mu$m. The laser beam focal spot size was 100 $\mu$m. This structure, which has a density 64% of solid, is loosely based on
the configuration studied by McKown et al [20] which incorporated both vertical struts and $45^\circ$ angled struts. The principal differences are the reduced size and higher density of the repeating units in the MS1 design. The reason for the move towards higher density is that an important aim of the work was to compare the experimental results with the predictions of 3D computer simulations. The maximum mesh size it is reasonable to use in the simulations is determined, to a large extent, by the smallest features in the structure; in other words, narrow struts require finer meshes. This led us to choose a nominal strut diameter of 0.4 mm, which was an appreciable fraction of the cell size (1 mm).

In order to characterize the SLM-processed 316L stainless steel, specimens for tensile testing were manufactured using the same SLM process parameters as the MS1 specimens. Dogbone specimens dimensioned as shown in figure 1 were loaded in tension in an Instron screw-driven test machine. The tensile stress–strain curve for the material is shown in figure 2, obtained using readings from the test machine load cell and a clip gauge. The stress at yield was estimated from these tests to be $\sim 640$ MPa (0.64 GPa).

Samples, consisting of 99.2 mm diameter porous discs of thickness 6 mm were prepared for plate-impact studies. A Scanning Electron Microscope (SEM) image of the top surface, (as viewed by the vertical arrow in figure 1) of one of the manufactured MS1 structures is shown in figure 3. It is clear that the actual structure exhibits features that are not seen in the computer-generated model. Undulations that appear on the surface tend to suggest melt pools of diameter in the range 150–350 $\mu$m, which seems consistent with the manufacturer’s estimate of 100 $\mu$m for laser beam diameter. Unmelted stainless steel particles can be seen at the borders between fused and unfused material.

Further information was obtained by examining structures which had been sectioned and etched. For example, in the high magnification SEM view of the boundary between melted and unmelted material in figure 4, particles are seen which have been partially melted by the laser beam. The grain size in the SLM material was estimated by taking a series of optical micrographs, as shown, for example, in figure 5, from which it was concluded that the average grain diameter was $\sim 5 \mu$m. According to the well-known Hall–Petch analysis [22, 23], a material with a small grain size tends to have a high flow stress. Kashyap and Tangri [24] measured the flow strength of 316L stainless steel in which the grain sizes from 3.1 $\mu$m to 85.7 $\mu$m were generated by rolling at room temperature. The strength value of $\sim 640$ MPa
Figure 3. An SEM showing the surface of an as-manufactured sample. Melt pools between 150 and 300 µm can be clearly seen, and are linked to the spot size of the laser.

Figure 4. An SEM image showing stainless steel particles that have been partially melted.

measured for SLM stainless steel is consistent with the values observed by Kashyap and Tangri for material with a grain size of ∼5 µm. We assume that the small grain size is a result of the very rapid sequential cooling experienced by the melt pools as the laser spot passes across them.

3. Experimental details

Three plate-impact experiments were conducted using the 100 mm diameter single-stage gas gun at The Institute of Shock Physics, Imperial College London. A reverse impact configuration similar to that chosen by Borg et al [5] was used in this study. The experiment is illustrated in figure 6. A 6 mm thick disc of the MS-1 structure was manufactured from 316L stainless steel using SLM. The disc incorporates a protective steel cylinder of length 6 mm, outer diameter 99.2 mm and wall thickness 0.5 mm. After manufacture by SLM, a lathe was used to machine a rebate at the leading edge of the disc, as shown in figure 6, to provide a light reflecting surface for velocity measurement using a Heterodyne Velocimetry (Het_V) probe [25]. The sample was mechanically attached to a polycarbonate sabot. This projectile impacted an instrumented 6 mm thick × 120 mm diameter 316L steel target at nominal velocities of 300, 500 and 700 m s⁻¹. The rear-surface velocity history of the steel target was monitored using
an array of three Het-V probes mounted on a diameter of 40 mm. A hole in the target plate allowed a fourth Het-V probe to be used to measure the projectile velocity. Note that since the diameter of the disc is much greater than its thickness, uniaxial strain conditions persist in the centre of the disc for the duration of the experiment. Based on computer simulations, the time at which release waves from the edges of the experiment would be expected to reach the central probe was $4.6 \, \mu s$ from impact time. The schematic distance versus time plot in figure 7 shows that the back surface of the target will be accelerated first by the wave generated by the initial impact and again, as illustrated by the green lines in the diagram, by the reflections from the interfaces between the compressed and uncompressed flyer and from the back surface of the flyer. As shown by the blue lines, eventually the velocity should be reduced by the rarefaction arising from the reflection of the initial compression wave through the porous material.

The Het-V measurements presented here were obtained using the ‘conventional’ configuration [26], where the beat signal was formed from homodyne mixing of the reflected Doppler shifted signal and back reflection from the probe. An IPG Photonics laser operating
near 1550 nm was used as the illumination source. Light was delivered and collected from the target using an Oz optics collimating probe with $-25$ dB back reflectance and a spot size of 220 $\mu$m, meaning it was sensitive to local perturbations in the free-surface velocity. The resulting beat signal was measured with a 12.5 GHz bandwidth receiver sampled at up to 50 GS$^{-1}$.

Impact tilt was not quantitatively measured for the experiments presented here due to the large-scale heterogeneity of the lattice structure. However, a qualitative measure of the impact condition was determined from a circular array of piezo-electric pins mounted flush with the impact surface of the steel target. Typical impact tilt for the ISP plate-impact facility is $<1$ mrad, providing confidence that the lattice structure is indeed loaded normal to the intended axis.

4. Experimental results

Raw data showing the rear-surface velocity history obtained from experiment MS1-1 (at an impact velocity of 300 m s$^{-1}$) is shown in figure 8 and unfolded data for the three experiments (at impact velocities of 300, 500 and 700 m s$^{-1}$) is shown in figure 9. The inset in figure 8 shows the raw PDV beat signal, which was used to calculate the power spectrum shown in the main figure. Het-V data is typically reduced in what is termed 'velocity mode' using short-time fourier transform (STFT) techniques, yielding a spectrogram displaying the distribution of spectral power density as a function of time and velocity. The STFT analysis leads to a trade-off between velocity uncertainty and temporal resolution. In this study, the projectile velocity and rear-surface velocity histories were extracted from the raw beat signals using a Hamming window function, a time duration of 82 ns and 30,000 frequency points in the STFT analysis. The relatively long analysis windows were necessary to distinguish between the various higher order surface reflections and provide an accurate determination of the velocities. The final velocity is extracted from a Gaussian fit to the peak of the power spectrum.

Figure 9 shows the rear-surface velocity histories obtained from the MS1 experiments. The traces have been positioned along the time axis so that they all start at the same time. Typically, each trace consists of an initial steep rise in velocity corresponding to the arrival of the elastic wave. The subsequent reduction in slope of the velocity trace indicates the transition to the plastic wave. This is followed by a plateau phase (termed here ‘first plateau’). Oscillations in velocity during the period of the first plateau are believed to be caused by the successive
collapse of the cells in the impactor. (See section 6.3). The amplitude of the cell-collapse waves decreases as the impact velocity decreases. Smaller, high frequency oscillations are noticeable on one of the 300 m s$^{-1}$ traces. It will be shown later that these probably result from the propagation of waves across the plane perpendicular to the shock direction. After 2–3 $\mu$s, the trace ramps up to a second plateau before lateral releases waves arrive. We assume this ramp arises as a result of wave reflections from the back surface of the flyer as illustrated schematically in figure 7.

5. CTH simulations

5.1. Outline

In order to gain an insight into the processes occurring during the dynamic collapse of the lattice structure, both 2D continuum and 3D ‘structural’ simulations in CTH were employed.
CTH is a multi-dimensional, multi-material Eulerian-based code developed by Sandia National Laboratories [21]. It is suitable for the simulation of large deformations and material distortions loaded under shock and high strain rate conditions. CTH incorporates many popular equations-of-state (e.g. Mie–Gruneisen) and strength models (e.g. [27, 28],) used to describe the behaviour of materials subjected to high-rate loading. It has well developed models for porous materials, namely the porous alpha ($P(\alpha)$) model [29, 30], (used in this study) and the $P(\lambda)$ model [30]. It also has a 3D capability together with the ability to read in descriptions of shapes defined using the surface triangle representation (stl) generated with computer aided design (CAD) software. CTH was used to perform both $P(\alpha)$ and 3D structural simulations of the MS1 experiments.

5.2. Continuum simulations

The so called $P(\alpha)$ model for modelling the porosity of materials under impact and shock conditions, was first proposed by Herrmann [29] and subsequently developed and extended by Carroll and Holt [30].

The fundamental assumption in this model is that the pressure in the porous material is expressed as

$$P = \frac{1}{\alpha} F \left( \frac{v}{\alpha}, E \right),$$

(1)

where $P_s = F(v_s, e)$ is the equation of state of the fully dense material and $\alpha = v/v_s$ is the distention ratio (the ratio of the porous material volume to that of the fully dense material at the same pressure and energy). $E$ and $v$ are the internal energy and volume per unit mass, respectively.

The compaction behaviour is then governed by functional form assumed to describe the variation of the distention ratio with pressure between its initial value $\alpha_0 = v_0/v_{s0}$ and the value 1.0 when the material is fully compacted. In the CTH simulations, we have used the simple form

$$\alpha(p) = 1 + (\alpha_0 - 1) \left[ \frac{P_C - P}{P_C - P_E} \right]^2,$$

(2)

where the crush strength, $P_C$, is the pressure at which complete compaction occurs and $P_E$ is the pressure at which plasticity first occurs. For the MS1 structure a crush strength of 1.9 GPa was estimated using the simplified Fischmeister-Arzt model [32]:

$$P_C = 2.97\sigma_y,$$

(3)

where $\sigma_y$ is the yield stress of the constituent particles. Note that the structure considered in this paper does not contain discrete particles, as assumed in [32], but instead consists of a regular connected structure. However, as a starting point it seemed justified to apply the Fischmeister-Arzt factor to the measured quasi-static yield strength of 0.64 GPa (see results in figure 2).

An estimate of $P_E$ the pressure which, when exerted on the porous material, would just initiate plastic flow, is provided by the work of Carrol and Holt [30] and Wu and Jing [33]:

$$P_E = 2\frac{\sigma_y}{3} \ln \frac{\alpha_0}{\alpha_0 - 1},$$

(4)

giving $P_E = 0.44$ GPa. Again, in applying the analysis in [30, 33], we have made the simplifying assumption that the structure may be treated as a solid matrix containing spherical voids.
Table 1. Constants used for the constitutive model.

| Property                                           | Value               |
|----------------------------------------------------|---------------------|
| Solid steel density                               | $\rho_0$           |
| Solid steel specific volume                       | $v_{s0}$           |
| Room Temperature                                  | $T_0$              |
| Sound speed                                        | $C_0$              |
| Slope of Hugoniot                                  | $S$                |
| Specific heat at constant volume                  | $C_v$              |
| Density of porous material                         | $\rho_0$           |
| Specific volume of porous material                 | $v_0$              |
| Elastic pressure of porous material                | $P_E$              |
| Crush pressure of porous material                 | $P_C$              |
| Poissons ratio                                     | $\nu$              |

| Constants used for the constitutive model.         |                     |
| Solid steel density                               | $\rho_0 = 7.90 \text{ g cm}^{-3}$ |
| Solid steel specific volume                       | $v_{s0} = 0.127 \text{ g cm}^{-3}$ |
| Room Temperature                                  | $T_0 = 298.1 \text{ K}$ |
| Sound speed                                        | $C_0 = 4.569 \text{ m s}^{-1}$ |
| Slope of Hugoniot                                  | $S = 1.49$ |
| Specific heat at constant volume                  | $C_v = 0.446 \text{ J g}^{-1} \text{ K}^{-1}$ |
| Density of porous material                         | $\rho_0 = 5.056 \text{ g cm}^{-3}$ |
| Specific volume of porous material                 | $v_0 = 0.198 \text{ cm}^{-3} \text{ g}^{-1}$ |
| Elastic pressure of porous material                | $P_E = 0.44 \text{ GPa}$ |
| Crush pressure of porous material                 | $P_C = 1.9 \text{ GPa}$ |
| Poissons ratio                                     | $\nu = 0.283$ |

Since the experimental configuration is radially symmetric it was modelled as two-dimensional (2D). Note that in $P(\alpha)$ simulations of a porous material, the shapes of the pores in an irregular structure or the cells shapes in a regular structure (e.g. MS1) are not explicitly modelled. Instead, the material is represented as a homogeneous region throughout which the porosity is uniformly distributed. As described above the effect of porosity is approximated using a macroscopic constitutive description which is judged to represent the bulk behaviour of the distended material.

The 316 Stainless Steel which forms the base material of the cellular flyer was modelled using a Mie–Gruneisen equation of state:

$$p = p_h(v) + \Gamma_0 \rho_0 (E - E_h(v)),$$

where

$$p_h(v) = \frac{1}{2} \frac{C_0^2 (v_0 - v)}{(v_0 - s(v_0 - v))^2}$$

and

$$E_h(v) = \frac{1}{2} \frac{C_0^2 (v_0 - v)^2}{(v_0 - s(v_0 - v))^2}$$

with constants as listed in table 1.

The mesh size for the $P(\alpha)$ calculations was 0.02 mm in all regions. The density of the cellular material was set to 64% of solid (5.056 g cm$^{-3}$).

The response of the solid stainless steel target was modelled using the Mie–Gruneisen EoS and the Steinberg Guinan strength model [27] together with the default constants in the CTH package.

5.3. 3D structural simulations

For the 3D structure simulations, hereinafter referred to as ‘3D’ simulations, the stl file used in the SLM manufacturing process was read into CTH, providing a geometrical representation of the lattice configuration including the detailed form of the individual cells. The stainless steel in the porous flyer was modelled using Mie–Gruneisen EoS and, (based on the strength measurement described in section 2), a constant flow stress of 0.64 GPa. The solid steel target was modelled using the same constitutive model that was used for the $P(\alpha)$ simulations described in the previous section.
Two types of 3D simulations, designated ‘full’ and ‘cut-down’, were run. In both cases, a uniform 0.05 mm mesh was employed giving \( \sim 8 \) elements through the 0.4 mm struts. A CAD package was used to define the MS1 structure as an array of triangles which was stored as an stl file. For the full 3D model two stl files were provided; the first contained a description of a single 1 mm thick layer of cellular material of diameter 99.2 mm and the second defined the protective surrounding ring of inner diameter 98.2 mm, wall thickness 0.5 mm and length 6 mm. The rebate at the edge of the disc seen in figure 6, which was used in the experiment to provide a reflective surface for velocity measurement, was not modelled as this would have required an additional stl file to be generated. Figure 10 shows computer-generated views of the structure. The complete flyer was constructed by first stacking six layers of cellular material together to create a disc of thickness 6 mm and overall diameter 99.2 mm, and then adding the outer protective ring.

To save computing time, the simulations whose results are presented in figure 13, and throughout much of section 6.3, were run using a cut-down model. Figure 11 shows a view in the impact, or axial, direction of the region of the cellular flyer modelled in the cut-down variant. Effectively it is made up of a group of four cells bounded by reflective boundaries. Dimensions in the axial direction are as shown in figure 6. Comparison of output obtained using the full and cut-down models showed only minor differences.

5.4. Results of 2D continuum simulations

The velocity profile measured at the back surface of the solid steel target are shown for comparison with the 2D continuum \( P(\alpha) \) calculations in figure 12. Since the individual cells of the MS1 structure are not modelled in the continuum simulations the oscillations observed in the experimental records are not reproduced in the simulations. The levels and relative timings of the initial shock, and the shock generated by the second interaction with the flyer–target interface (as illustrated in the distance versus time plot in figure 7), are well matched by CTH. However, in the 700 m s\(^{-1}\) experiment, the \( P(\alpha) \) model exhibits a release at \( \sim 4 \mu s \) which is not observed in the experiment. This suggests that the wave path shown in blue in figure 7 travels too fast in the simulation. A possible explanation is that the porous material of the flyer is densified more in the simulation than in the experiment.

A 1D \( P(\alpha) \) simulation and a series of 2D \( P(\alpha) \) simulations were run to estimate the time for which the Het-V measurement remains one-dimensional. Surface velocities were monitored
at a radius of 20 mm and the diameters of both the flyer and the target plate were varied. It was found that with a 49.6 mm radius plate (as used in the experiment) the trace begins to diverge slightly from true 1D behaviour at ~3 µs after the shock reaches the rear surface of the target. This suggests that waves from the edges do not affect the first plateau but do have a very small effect on the second plateau.

5.5. Results of 3D structural simulations

The 3D CTH simulations are shown for comparison with the experiments in figure 13. It is seen that for all three experiments the levels of the first and second plateaus are reasonably well matched. The simulations also match the frequencies of the oscillations superimposed on the experimental traces. However, at the highest velocity, the oscillations generated by sequential
collapse of the cells appear out of phase with the experiment. In the 500 m s$^{-1}$ experiment, the calculated amplitude of the oscillations is significantly greater than that observed.

6. Discussion

6.1. Outline

The waves transmitted into solid steel targets by the impact of the MS1 cellular structure at velocities of $\sim$300, 500 and 700 m s$^{-1}$ have been measured and the three experiments have been simulated using CTH. 2D continuum simulations using the $P(\alpha)$ porosity model gave a good match to the average levels of the surface velocities of the target plate. Since the $P(\alpha)$ model treats the material as a continuum the oscillations caused by the successive collapse of the cells were not reproduced. However, the good match provided by CTH to the averaged experimental results encouraged us to assume that other features of the material response, (which were not amenable to experimental measurement), would also be correctly modelled by CTH, thereby providing further information on the state parameters in the shocked samples. CTH also offers insight into the microscopic processes taking place within the material. An understanding of such processes is fundamental to our understanding, not only of energy absorption but also phenomena such as shock compaction of granular materials [34] and hot spot formation in shocked granular explosives [35].

6.2. Continuum simulations—state parameters

A number of useful conclusions regarding the response of the MS1 structure can be drawn from the $P(\alpha)$ continuum simulations. A time sequence for the CTH simulation of the 300 m s$^{-1}$ experiment showing the propagation of the elastic and plastic waves in the porous flyer and the solid steel target is shown in figure 14. As expected the elastic wave which propagates back into the flyer has an amplitude equal to the elastic pressure of 0.44 GPa assigned to the MS1 structure as described in section 5.2.

Table 2 lists the normal stresses and the specific volumes in the elastic and plastic regions calculated by CTH for all three experiments. As observed by other authors the normal stress
behind the plastic shock increases as the impact velocity increases. The shock conservation equations, may be used to derive the other state parameters as desired [10–14, 38]. For example, the internal energy increase, $\Delta E$, due to the passage of a shock which increases the normal stress and specific volume in the sample from $\sigma_1, v_1$ to $\sigma_2, v_2$ is given by

$$\Delta E = \frac{1}{2} (\sigma_1 + \sigma_2) (v_1 - v_2).$$

(8)

For the elastic wave the initial stress, $\sigma_1$, is zero, and the initial specific volume, $v_1$, is 0.198 cm$^3$ g$^{-1}$ giving the internal energy in the elastic wave $\sim$0.04 J g$^{-1}$. Calculated values of the internal energy in the plastic wave are given in table 2. (Note that 1000 J g$^{-1}$ $\equiv$ 1 GPa cm$^3$ g$^{-1}$).

### 6.3. 3D Simulations—qualitative observations

It has been shown that 3D simulations run using the CTH hydrocode have matched the main features of the velocity wave transmitted through the target in the configuration shown in figure 6 reasonably well. The match to experiment achieved by CTH is comparable to that obtained in similar studies with irregular metal foams [5]. A key objective of our work is to evaluate the use of SLM structures as a vehicle to understand the mechanisms of energy absorption, and thereby to contribute to the optimization of energy absorbing structures. We
Figure 15. A sequence of material plots for a $300 \text{ m s}^{-1}$ impact, illustrating the sequential collapse of the voids in the MS1 structure. As the incident shock wave reaches each cavity a pressure trough followed by a peak is propagated into the target.

also believe the work to be relevant to other areas in which the microscopic flows occurring in impacted heterogeneous materials are important. Examples are the shock consolidation of porous materials [34] and the generation of hot spots in heterogeneous explosives [35].

Figure 15 shows a sequence of material plots illustrating the evolution of the structure as viewed on the section depicted by the white arrow in figure 10(a) for an impact velocity of $300 \text{ m s}^{-1}$. Note that in this sequence and those that follow, an initially stationary solid target is impacted by a porous flyer approaching from the left. Therefore, the crush wave in the flyer propagates to the left. In figure 15, the numbers (0.5–2.4) give the time in microseconds from impact. It can be seen that, viewed in this section, each 1 mm cell has two cavities, labelled large (L1 to L4) and small (S1 to S3). The partial collapse of cavity L1 is shown in the sequence on the left of figure 15; a similar process, occurring $\sim1.5 \mu\text{s}$ later, collapses cavity L2. A full sequence would show that the small cavities S1 to S2 undergo a similar collapse process. The process by which collapse of the cavity generates a pulse in the transmitted wave is as follows. As the compression wave meets the surface of the cavity, a radial release wave is generated which propagates both laterally and back in the direction from which the wave has come. Eventually, this release wave reaches the back surface of the target where it produces a dip in the velocity field. On full collapse of the cavity a compression wave is generated which propagates radially outward resulting in an increase in pressure. The successive collapse of the large and small cavities generates a roughly sinusoidal ‘primary’ wave into the solid target with a peak to peak time of $\sim0.75 \mu\text{s}$.

Figure 16 shows a series of internal energy maps corresponding to the $500 \text{ m s}^{-1}$ experiment. As in the density plot of figure 15, large and small cavities are visible. Since the impact velocity ($\sim500 \text{ m s}^{-1}$) is greater than that in the experiment depicted in figure 15 the cavities collapse in a different way. In the higher velocity case, as each cavity collapses it generates a jet which propagates in the direction of the shock in the lattice. Remember that the cellular component travels from left to right before impacting a stationary solid steel target. Therefore, the shock in the cellular material travels from right to left. As shown in figure 17, according to CTH, the intense plastic flow within the jet raises the temperature in the jet to more than 800K.

Figure 18 shows a map of cell velocities at 0.5 $\mu\text{s}$ after a $300 \text{ m s}^{-1}$ impact. The interface between the porous flyer and the steel target was originally at 6 mm and the back of the target was at 12 mm. At 0.5 $\mu\text{s}$, the flyer–target interface has moved $<1 \text{ mm}$ from its original position.
Figure 16. Internal Energy maps for an impact velocity of 500 m s\(^{-1}\). The units are erg g\(^{-1}\) (note that \(4 \times 10^9\) erg g\(^{-1}\) = 400 J g\(^{-1}\)).

Figure 17. Temperature plot at 500 m s\(^{-1}\).

Figure 18. Simulation of a 300 m s\(^{-1}\) experiment showing a velocity map at 0.5 \(\mu\)s from impact. The blue regions indicate zero velocity. Velocities \(>40\) m s\(^{-1}\) appear red (therefore the waves reflecting into the projectile are not visible).

The velocity scale here was chosen to optimize the visibility of the relatively low velocity waves in the target. The elastic and plastic waves can be clearly seen in the plot. The elastic wave appears fairly smooth but the plastic wave exhibits perturbations corresponding to the cellular structure of the flyer. As expected the velocity field shows periodicity in both the axial (\(z\)) and transverse (\(y\)) directions. The time sequence in figure 19 shows that the surface velocity does indeed vary with space and time across the surface that is monitored in the experiment.

As noted in section 2, experimentally it would be very difficult to align the velocity diagnostic at a specified location relative to the cell structure. Therefore, any perturbations in the wave profile in the \(x-y\) plane can lead to uncertainty in the comparison between experiment and simulation. Simulations were run to provide a picture of the likely errors associated with this velocity measurement. As shown in figure 20, velocities at the back face of the target were computed at different positions relative to the cell structure. Typical time variations at the chosen points are shown in figure 21. It is seen that the secondary oscillations of amplitude
Figure 19. Simulation of a 300 m s\(^{-1}\) experiment. Velocity maps at the back face of the target. The pattern changes with time as wavelets propagate in the \(x-y\) plane.

Figure 20. Velocities at the back face of the target were computed at the four positions indicated.

\(\sim 8\) m s\(^{-1}\) and wavelength \(\sim 0.15\) \(\mu\)s resulting from wave propagation perpendicular to the axis of the experiment are significantly different at the different monitoring points. However, the larger, primary waves generated by the collapse process do not appear to be significantly affected by the position in the \(x-y\) plane at which the waves are monitored. Therefore, it was judged that the differences in the traces resulting from different positions relative to the cell were small compared with the main features caused by the cellular structure. In summary, we concluded that comparison between the simulations and the experiments would provide a useful measure of the ability of the code to compute the dynamic response of cellular structures.

6.4. Microjetting

The high resolution 3D simulations presented in this paper provide a picture of the developing pattern of parameters such as stress, strain, velocity and energy within the material. We hope this will contribute to areas of study apart from energy absorption, for example, shock compaction of granular materials and the generation of hot spots in porous explosives. CTH allows the total kinetic energy in each cell to be audited. For a cell containing \(N\) materials the total kinetic energy in the cell may be expressed as follows:

\[
E_{\text{kin}} = \frac{1}{2} \sum_{i=1}^{N} \rho_i u_i^2 F_i, \quad (9)
\]
Figure 21. Simulation of MS1-45-1: impact velocity 300 m s\(^{-1}\). The four traces show the velocities computed at the four locations aligned with the lattice as indicated in figure 20.

Figure 22. Time sequence of total kinetic energy density for an impact of the MS1 lattice at 500 m s\(^{-1}\). The total kinetic energy is defined according to equation (10). The units are ergs g\(^{-1}\).

where \(u_i\) is the speed, or velocity modulus, of the cell (termed \(V_{\text{mag}}\) in CTH), and \(\rho_i\) and \(F_i\) are the density and volume fraction of the \(i\)th material.

If the cell contains only one material or one material plus void, as in our case, then for each cell:

\[
E_{\text{kin}} = \frac{\rho u^2 F}{2},
\]  

(10)

where \(u\) is the velocity modulus and \(\rho\) and \(F\) are the density and fraction of the cell occupied by solid, respectively.

The CTH sequence in figure 22 shows the developing kinetic energy field in a flyer impacting at 500 m s\(^{-1}\). Comparing the kinetic energy and internal energy fields show that the two fields develop in similar ways.

The energy plot in figure 22 suggests that intense flows associated with void closure are important mechanisms for the absorption of energy during the impact loading of cellular
material at velocities of a few hundred metres/second and beyond. In particular, it is evident from simulations not shown in this paper that as the impact velocity is increased the velocity, temperature and internal energy of the jets increases. The phenomenon is similar in principle to the concept of microkinetic energy observed in studies of the compaction of granular materials. Microjetting was clearly illustrated in papers by Benson et al [34] and Eakins [36, 37]. A multi-material Eulerian program (Benson et al [34]) was used to compute the response of an assembly of metal spheres to impact loading. In particular, it was noted that the material in shocked heterogeneous materials will in general have a finite component of velocity perpendicular to the shock direction. The energy associated with this perpendicular velocity component was termed microkinetic energy. Benson et al’s simulations showed that the microkinetic energy generated in a porous material subjected to impact loading increases as the pressure to which the system is loaded increases [33]. It was noted that microkinetic energy plays a key role in bonding between particles during shock densification and in the initiation of chemical reactions and phase transitions.

CTH allows the components of velocity and kinetic energy in the direction of the shock, z, and the two orthogonal directions x and y to be output both numerically and in graphical form. The computed situation in a 500 m s$^{-1}$ MS1 system at 2 $\mu$s from impact is shown in figure 23. Frames (a), (b) and (c) show velocity magnitude ($V_{mag}$), $V_z$ (in the shock direction) and $V_y$ (in one of the transverse directions), respectively. Frames (d), (e) and (f) show similar plots for kinetic energy. Note that since the total kinetic energy should equal the sum of the kinetic energies in the three orthogonal directions, the energy in plot (f) should be half the difference between the energies in plots (d) and (e). Plots (c) and (f) show that the transverse velocity and transverse energy are generated in localized regions or ‘hot spots’ as the shock reaches a void. The sequence at the bottom of figure 24 shows that the kinetic energy hot spots propagate with the compaction front, oscillating in shape and size as they do so.

The simulations run by Benson and coworkers suggested that the amount of transverse kinetic energy increased as the impact velocity increased. In the sequence at 700 m s$^{-1}$ in figure 24, it is seen that the size of the hot spot has, as expected, increased relative to the 500 m s$^{-1}$ simulation.
Figure 24. A time sequence showing the distribution of transverse kinetic energy. CTH sequences were run at 500 m s\(^{-1}\) (top) and 700 m s\(^{-1}\) (bottom).

Figure 25. Variation of transverse kinetic energy generated in the cut-down region depicted in figure 11.

CTH allows the total kinetic energy in a chosen region, (or array of cells) to be audited. If all the cells, 0 to c, in a chosen volume of the system contain only one material (of density) or one material plus a void (as in our case) the total kinetic energy, \(E_{\text{kin}}\), in that region is given by summing equation (10) over all cells in the region:

\[
E_{\text{kin}}^{\text{tot}} = \frac{1}{2} \rho \sum_{c} u_{c}^2 F_{c},
\]

where \(F_{c}\) is the fraction of the cell occupied by a solid of density \(\rho\) and velocity modulus \(u_{c}\). The total kinetic energy for the ‘cut-down’ region defined in figure 11 was calculated for impact velocities of 500, 700, 900 and 1100 m s\(^{-1}\). The transverse kinetic energies are plotted against time from impact in figure 25. As expected from the results of Benson et al [34] it was found that the transverse energy generated in the system increased as impact velocity increased.
7. Conclusions

Selective Laser Melting was used to fabricate a cellular structure, designated MS1, which consists of intersecting 316L stainless steel rods. Tensile tests performed on dogbone shaped test specimens manufactured using the same conditions as were used for the cellular structures revealed the yield strength of the SLM material to be $\sim 0.64$ GPa. The shock delivered to a solid target by a gas-gun-driven flyer with the MS1 structure has been measured experimentally using a Heterodyne Velocimetry (Het-V) technique. It was found that all of the traces consisted of a small elastic precursor followed by a plastic wave which took the velocity to a first plateau of duration about one microsecond. A second reflection from the flyer–target interface then took the trace up to a second velocity plateau. For all of the experiments the first plateau exhibited roughly sinusoidal oscillations.

Continuum simulations of the experiments were run using the $P(\alpha)$ model [29, 30] in conjunction with the Sandia National Laboratories code CTH. Values for the crush pressure and elastic pressure required by the model were estimated from the measured yield strength of a test piece of solid SLM steel. It was found that a good match to the average levels and timing of the plateaus were obtained by CTH. The experimentally observed oscillations were, of course, not reproduced by the $P(\alpha)$ model.

The $P(\alpha)$ simulations allow the state parameters behind the elastic and plastic waves which propagate into the MS1 sample following impact to be estimated. As found in previous research, (see for example [10]), the stress in the impact direction increases as the impact velocity increases. As expected the state parameters in the shocked regions are related by the equations derived from assumptions of conservation of mass, momentum and energy for shock jumps. The internal energies generated behind the plastic waves in the cellular samples were estimated from the continuum simulations to be $56 \text{ J g}^{-1}$, $112 \text{ J g}^{-1}$ and $183 \text{ J g}^{-1}$ for the experiments at $300 \text{ m s}^{-1}$, $500 \text{ m s}^{-1}$ and $700 \text{ m s}^{-1}$, respectively.

Three-dimensional ‘structural’ CTH calculations were run in which stl files used to manufacture the MS1 samples were imported into CTH. In this case, the detailed, dimensioned structure of the lattice was modelled. These simulations gave a reasonable match to all of the features observed in the experiments including the oscillations which were superimposed on the first and second velocity plateaus at the back surface of the solid steel target. The 3D simulation provided insights into the processes at play in the shocked lattice. As the compression wave reaches a cavity a release wave followed by a compression wave is generated. The array of cavities in the MS1 structure thereby generates stress oscillations which propagate in all directions. As these waves reach the back surface of the target, they cause the velocity oscillations observed in the experiment.

Comparing 3D simulations of the lattice response to impacts at the three experimental impact velocities suggest that, as the impact velocity is increased, intense flows or ‘microjets’ are generated within the cavities. Understanding this microjet formation may be important for optimizing cellular materials for absorbing shock and impact energy. The microjetting phenomenon is akin to the shaped charge jets often observed when explosives drive angled plates together. (See for example [39]). Further, in agreement with previous researchers [34, 36, 37], we note that particularly at the higher impact velocities, the shocked material has a finite component of velocity perpendicular to the shock direction. The transverse component of energy, which may be termed ‘microkinetic energy’, is believed to be important in the understanding of phenomena such as the compaction of granular materials and the generation of hot spots in shocked explosives.

We recognize that the microjets seen in the 3D simulations may not occur in reality. Therefore, in future work, we will attempt to confirm the existence of microjets
in shocked samples of structures similar to those described here, using flash x-ray methods.

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