A novel graded density impactor

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A novel graded density impactor

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Abstract. Ramp loading using graded-density-impactors as flyers in gas-gun-driven plate impact experiments can yield new and useful information about the equation of state and the strength properties of the loaded material. Selective Laser Melting, an additive manufacture technique, was used to manufacture a graded density flyer, termed the “bed of nails” (BON). A 2 mm thick x 100 mm diameter solid disc of stainless steel formed a base for an array of tapered spikes of length 6 mm and spaced 1 mm apart. The two experiments to test the concept were performed at impact velocities of 900 m/s and 1100 m/s using the 100 mm gas gun at the Institute of Shock Physics at Imperial College, London. In each experiment a BON flyer was impacted onto a copper buffer plate which helped to smooth out perturbations in the wave profile. The ramp delivered to the copper buffer was in turn transmitted to three tantalum targets of thicknesses 3, 5 and 7 mm, which were mounted in contact with the back face of the copper. Heterodyne velocimetry was used to measure the velocity-time history, at the back faces of the tantalum discs. The wave profiles display a smooth increase in velocity over a period of ~2.5 μs, with no indication of a shock jump. The measured profiles have been analysed to generate a stress strain curve for tantalum. The results have been compared with the predictions of the Sandia National Laboratories hydrocode, CTH.

1. Introduction

It is well known that experiments to measure the changing profiles of ramp compression waves can provide useful data on the material through which the wave propagates (for example see [1, 2]). One way of generating a ramp wave is to impact a disc of the specimen material with a flyer whose density is low at the leading face but increases with distance from that face. In this paper we explore the potential of a graded porosity flyer manufactured by selective laser melting (SLM) to generate ramp waves in a target. The procedure was as follows. A stainless steel flyer was designed in which the average density varied over a distance of 6 mm. The region of varying density was attached on a 2 mm thick solid base (also manufactured by SLM). The Sandia National Laboratories code CTH was used to compute the wave delivered to a series of solid targets at a range of impact velocities. Based on this computational study experiments were designed with the objective of demonstrating the bed-of-nails concept for generating ramp waves and of determining the validity of CTH to compute the configuration. Experiments were performed and the results were compared with CTH. A simple analysis was used to construct stress vs volume relationships for the target material.

2. The “bed of nails” concept

A bed-of-nails flyer was manufactured by SLM. In the procedure used in this work a ~40 µm layer of 316L stainless steel powder was deposited on a base plate. A laser beam with a diameter of ~40 µm was scanned over the layer, melting it in a pattern specified by an stl file. The structure was built-up by adding more layers. An individual “nail” is shown in figure 1 (a). It has a parabolic profile giving a linear variation of average density with depth. The base of the nail is a 1 mm square. The nails are centred on a 1 mm x 1 mm grid and sit on a 2 mm thick base of solid stainless steel.

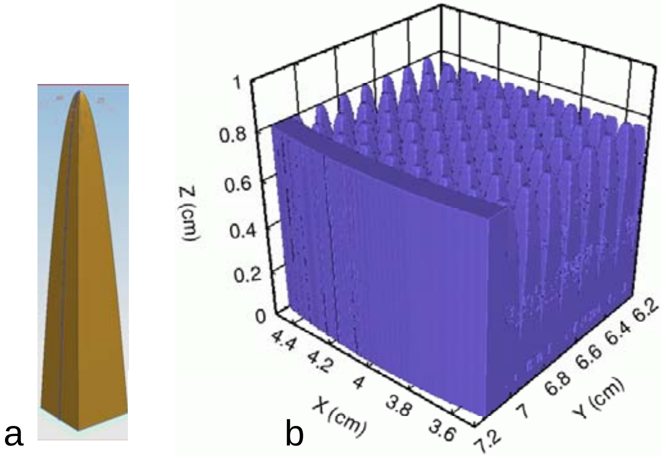

Figure 1. (a) The parabolic profile of the “nail” gives a linear density variation. (b) an array generated in CTH: the nails sit on a 2 mm solid base.

3. CTH simulations

A series of simulations were run using CTH with the aim of estimating the rate of pressure rise and the smoothness of the wave delivered to a range of target materials. Initially, simulations were based on the expected experimental flyer which measured 99.4 mm diameter x 8 mm thick. Later in the study simulations were reduced to a 2 mm x 2 mm element with reflective boundaries. The mesh size for both the full and reduced simulations was 50 µm.

It was found that, if no strength was assigned to the target, the waves propagating into the target were unacceptably perturbed, with violent pressure oscillations in both the propagation direction and the perpendicular plane. However, assigning rate-dependant strength to the target generated a much smoother profile. A CTH depiction, run as a full array, of the wave delivered to a 16 mm thick copper target with a Johnson Cook [3] rate-dependant strength model, is shown in figure 2. Although perturbations are just visible in the target these appear trivial compared with those in the impactor.

Figure 3 shows a series of pressure vs distance profiles in a 16 mm copper target impacted at 900 m/s. Since the target was impacted on its left face the waves propagate to the right. As indicated by the dashed line the pressure in the wave rises by ~ 0.45 GPa/mm (equivalent to ~ 1.8 GPa/µs).

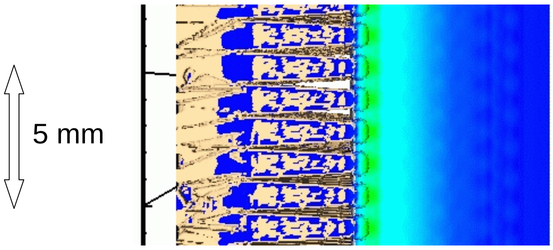

Figure 2. Normal (horizontal) stress plot showing 600 m/s impact of BON onto 16 mm copper.

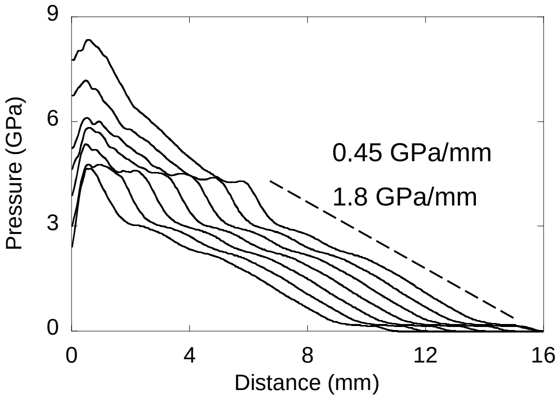

Figure 3. Wave profiles in a 16 mm copper target impacted at 900 m/s. The traces are 0.2 µs apart.

Further calculations were run in which the ramp wave was transmitted via a 6 mm copper smoothing layer to a 16 mm Tantalum target as shown in figure 4 (a). In these simulations the computing time was significantly reduced by confining the setup to a 2 mm x 2 mm region of the flyer as shown in figure 5. Pressure vs. distance profiles for those simulations are shown in figure 6, and velocity vs. time profiles at 3, 5 and 7 mm into the tantalum are shown in figure 7.

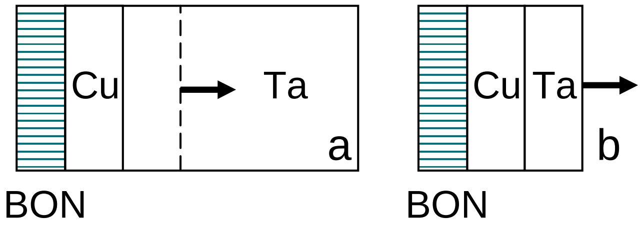

Figure 4. (a) & (b): setups for simulations to determine in-situ and free surface particle velocities.

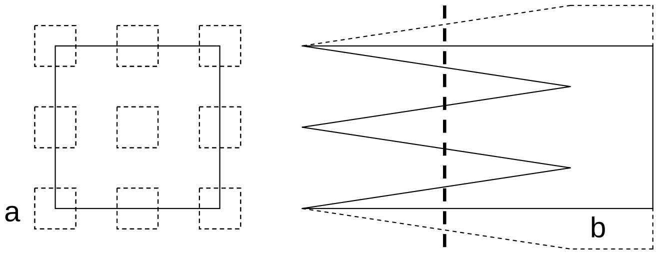

Figure 5. The “cut-down” CTH model. In the end view shown in (a) the solid lines are modelled as reflective boundaries.

Simulations were run, as shown in figure 4 (b) in which the back-surface velocity of tantalum samples of thickness 3, 5 and 7 mm were computed. In figure 7, the surface velocities have been divided by 2 to allow comparison with the corresponding in-situ velocities. It is seen that to a close approximation the in-situ velocity is half the free surface velocity. This approximation will be used later to analyse the experimental results.

Based on the results seen in figures 6 and 7 it was judged that the configuration depicted in figure 4 (b) should form the basis of an experimental study.

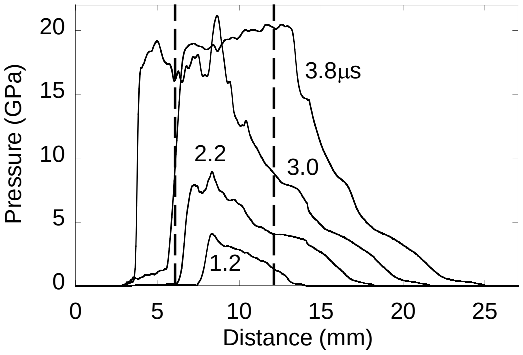

Figure 6. Pressure plots for 900 m/s impact onto a target consisting of 6 mm copper plus 16 mm of tantalum. The dashed lines at 6 and 12 mm show the initial positions of the BON/Cu and Cu/Ta interfaces respectively.

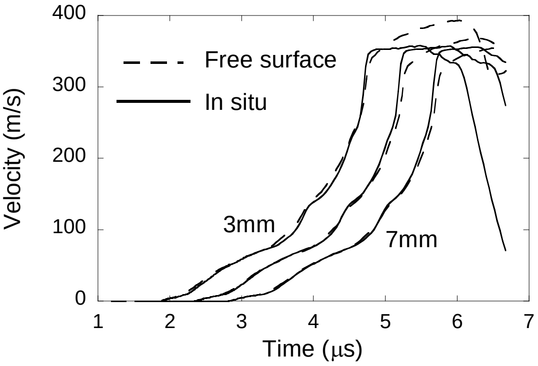

Figure 7. CTH comparisons of in-situ and free surface velocities.

4. Experiments

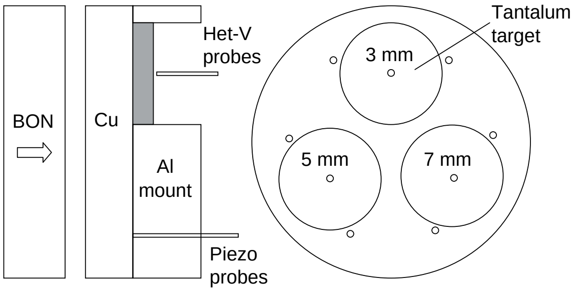

Figure 8. Experimental set-up.

The experimental set-up is shown in figure 8. Surface velocities were measured using the Het-V system [4] and tilt and impact times were measured using piezo-electric probes. A photograph showing the leading part of the flyer is shown in figure 9. As shown, the shoulder of the flyer was machined back to allow the impact velocity to be measured using Het-V probes.

5. Results

The measured surface velocities for the three target thicknesses are shown for comparison with the CTH predictions in figure 10. It is interesting that the measured traces appear smoother than the CTH traces. In the CTH traces there is a noticeable jump in velocity at ~2 μs after wave arrival. Examination of the corresponding CTH velocity maps, in figure 11, suggests that the jump arises from a reflection at the BON/copper interface as shown in the inset x-t diagram in figure 10. We do not know why this feature is absent in the experimental traces, but it is possible that the interface presents a more dispersed density profile in the experiment than that computed. This could reduce the sharpness of the reflected wave.

If it is assumed that the free-surface velocities are twice the in-situ velocities, as suggested by the CTH calculations in figure 7, the shock wave conservation relations can be used to generate longitudinal stress vs longitudinal strain plots corresponding to each of the three pairs of results available from the data. The derived plots are shown in figure 12. It is seen that the three curves are slightly different from each other suggesting that there are some errors in the method. Alternatively it is possible that some of the nails (or groups of nails) have a slightly different composition from others. This could lead to differences in the waves delivered to the different tantalum samples.

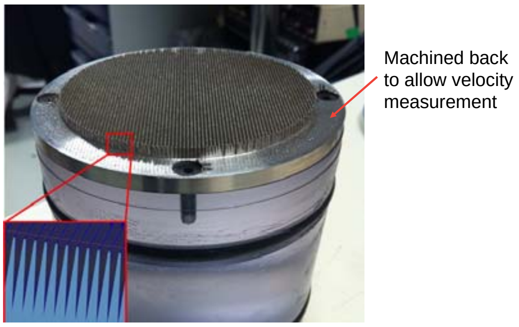

Figure 9. Photograph of BON flyer.

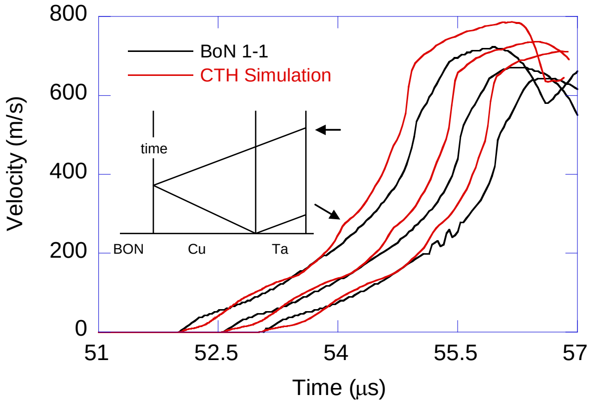

Figure 10. Results of 900 m/s experiment for comparison with CTH simulation.

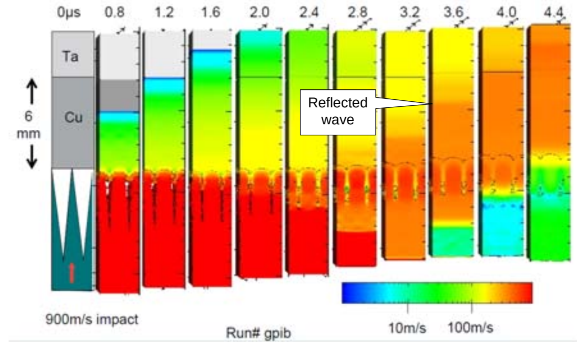

Figure 11. Velocity plots for a 900 m/s impact onto a target consisting of 6 mm of copper and 3 mm of tantalum.

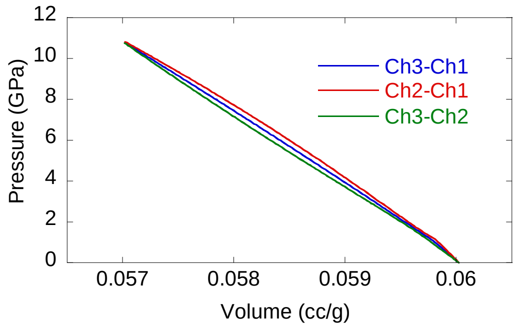

Figure 12. Stress vs. volume plots for the three pairs of records provided by the 900 m/s experiment.

6. Conclusions

An stl file was generated for a flyer in which the average density varies linearly over a distance of 6 mm. CTH suggested that, at 900 m/s, this would deliver a pulse with a rise time of ~2 GPa/μs to a copper target. Experiments were designed to evaluate the validity of CTH in this regime. Het-V was used to measure the free surface velocities of tantalum targets of thickness 3, 5 and 7 mm. The measured profiles appeared reasonably smooth and in broad agreement with the simulations. However the simulations suggested that the profile would be affected by reflections from the impact interface. Assuming that the surface velocity is twice the in-situ velocity allows stress vs. strain curves to be derived.

Acknowledgements

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