Ramp wave generation using graded areal density ceramic flyers and the plate impact technique

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Abstract. A requirement exists to generate realistic insults in energetic targets, for example ramp loadings leading to shock waves. This paper examines the development of a ceramic flyer ramp wave generation technique. Ceramic stereolithography was used to produce fully-dense, graded areal density alumina ceramic flyers. These flyers consisted of multiple square pyramids arranged on a solid base. The gas gun plate impact and electromagnetic particle velocity gauge techniques were used to observe the ramp waves generated when the flyers impacted a Kel-F 81 polymer target. Ramp waves of varying properties were successfully generated in the targets, and good agreement was obtained with 3D hydrocode modelling.

1. Introduction

A requirement exists to generate ramp loadings in energetic targets; this is to simulate realistic insults leading to complex shocks entering targets. It is well reported in the literature that energetic materials react differently to a ramp loading as opposed to a sustained shock of the same peak amplitude. Setchell et al. [1] showed that a ramp wave acts to delay initiation of a conventional high explosive in this scenario.

This paper details the development of a novel ramp wave generation system and gives initial experimental and simulation results. Kel-F 81 (PCTFE) polymer was used to simulate the explosive.

2. Concept

Experimental constraints dictated that the ramp wave generation method had to be compatible with both the gas gun plate impact and electro-magnetic particle velocity gauge (PV gauge) [2] techniques. Due to the complexities encountered when using metallic flyers or barriers with the particle velocity gauge system [3,4], it was decided that the materials used had to be non-metallic and non-conductive. This is due to metallic flyers or barriers giving rise to voltage perturbations in the particle velocity (PV) gauge output which are difficult to remove without compromising the quality of the data. Additionally the available launcher capabilities meant that relatively high impedance ceramics were the only realistic option for generating the required peak impact pressures to initiate the explosives of interest.
Once the material had been selected, various options were examined for producing a flyer that would generate a ramp wave in the target. The most straightforward method was to produce a solid ceramic flyer using layers of varying material (e.g. alumina and zirconia) or layers of varying porosity of the same material. Examples of this approach are found in the work of Barker [5] and Orlikowski et al. [6]. Additionally the possibility of using spark plasma sintering as a manufacturing technique was considered. However it was decided that this avenue would present a protracted development route, considering the limited in-house expertise in this field.

An alternative avenue was graded areal density. This technique, as reported by Winter et al. [7], uses a flyer with a graded areal density (mass per unit area). An example of this is a solid base with multiple spiked protrusions (‘bed of nails’). This flyer is then paired with a buffer plate of a similar material in contact with the target (see figure 1(a)). The intent is that the flyer impacts the buffer and multiple wavelets form around the tips of the spikes. These wavelets then coalesce in the buffer and the target undergoes a shockless compression loading path that eventually leads to the formation of a shock. The buffer also acts to prevent the spikes from penetrating the target. The elegance of this method is that the spike and buffer parameters can easily be altered to produce ramps of different magnitude and duration. Winter et al. [7] utilised this method with metallic flyers and the selective laser melting manufacturing process, however due to the aforementioned restrictions, a ceramic manufacturing method was employed here.

Figure 1. (a) ‘Bed of nails’ concept and (b) manufactured sample mounted on an acetel gas gun sabot.

Rapid prototyping conducted by Tech Assessment and Transfer Inc. (MD, USA) allowed manufacture of fully dense alumina ceramics. These were produced using a Toll Ceramic Stereolithography (CSL) technique which included a sintering step. Figure 1(b) shows an example of a spiked disc mounted on a sabot.

3. Graded Areal Density Flyers
The flyer designs produced were based on input from the manufacturer on the feature resolution, spike shapes and accuracy obtainable. Small feature resolution of ~127 µm and surface roughness (Ra) of ~30 µm were quoted. For the initial batch it was decided to test the limits of the process and aim to produce flyers that would generate a long and shallow ramp wave. While not suited to initiating conventional explosive targets, these would adequately demonstrate proof of concept and would provide a limit to one end of the parameter space available (the other extreme being a conventional solid flyer). This type of scenario would also test the hydrocode modelling used to assist with the initial designs. The two initial designs of flyers are shown in figure 2 and were used with 5 mm thick buffers.
Figure 2. Initial flyer designs – (a) 10 mm spike height and (b) 5 mm spike height.

The initial spike parameters were modelled using 2D and 3D ANSYS Autodyn® models [8] to give confidence that a ramping wave would be produced. Metrology on the manufactured flyers was carried out using immersion density testing and X-ray micro-computed tomography (Micro-CT). The flyers were found to be fully dense (3.74 g/cc), although the mass of the flyers was slightly different from the theoretical weight of the design supplied to the manufacturers. The difference was <2% for the flyers and discs; on average the manufactured samples were lighter than their expected mass. The Micro-CT showed that the flyers were solid and did not have any visible internal cracks or voids, with the shape of the spikes found to be a close match for the supplied design. However some minor defects around the tips were noted, which generally took the form of slightly asymmetric tips to the pyramids.

4. Experimental Results
A number of experiments were performed on the 50 mm bore single-stage light-gas gun at Cranfield University. The experiments utilised the standard magnetic particle velocity gauge technique [2] with a Kel-F 81 (PCTFE) target. The magnetic field strength was 195±4 mT and was provided by NdFeB N50 permanent magnets. The PV gauge used consisted of copper tracks on a polyamide substrate and had 7 gauge elements with 2 shock trackers.

A set of example results is presented in figure 3 and key features discussed below.

Figure 3. Experimental results from impact using 5 mm spike height flyer system at (a) 536 ms⁻¹ and (b) 957 ms⁻¹ (see figure 2(b) for flyer details). Trace labels indicate the distance of the gauge element relative to the target/buffer interface (mm).

Figure 3 shows a set of results for the 5 mm spike height flyer system. A shockless compression leading to a shock wave can be observed entering the target and at both impact speeds a gradient
change occurs during the subsequent rise. This is thought to be due to reloading in the buffer disc. In both cases release waves from the edge of the impactor appear to prevent the ramp from reaching its full magnitude. It was also noted that the shock trackers (not shown) did not function effectively, as they are dependent on a sharp fronted shock to operate; however these were still useful as ‘tilt pins’. Shock pressures were calculated [Kel-F EOS taken from 9] and are shown in figure 4 for the high-velocity impact.

Figure 4. Kel-F target shock pressure from impact using a flyer with 5 mm spike height flyer system at 957 ms⁻¹ (see figure 2(b) for flyer details). Trace labels indicate the distance of the gauge element relative to the target/buffer interface (mm).

5. Comparison to Modelling
The experimental results were compared to representative simulations run using ANSYS Autodyn®. The 3D lagrangian simulation parameters used are listed in table 1. Unless otherwise noted equation of state (EOS) parameters are from the standard library, Al₂O₃ 99.7 was used to represent the rapid prototype ceramic as it represented the nearest match in the standard material library [8].

Table 1. Autodyn parameters.

| Parameter          | Part                      | Ceramic Flyer | Ceramic Buffer | Kel-F Target   |
|--------------------|---------------------------|---------------|----------------|----------------|
| Material model     | Ceramic Flyer             | Al 99.7       | Al 99.7        | Kel-F [9]      |
| Mesh               | Graded 0.0156 mm³ to 1.56 x 10⁻⁵ mm³ | 0.0156 mm³     | 0.0156 mm³     | 0.0156 mm³     |
| Strength model     | Johnson-Holmquist (JH.) [8,10] | JH.           | Von Mises [11] |
| Failure model      | None                      | JH.           | None           |
| Erosion strain     | 3                         | 3             | 3              |

The PV gauge results from experiments were compared with velocity and pressure data from virtual gauges embedded in the model. Figure 5 shows the comparison for the 5 mm flyer system at two different impact speeds. The average of several virtual gauge points was used to simulate a finite length PV gauge element.
The simulation was found to be sensitive to the erosion strain used. An overly low deformation limit resulted in considerable portions of the spikes being removed shortly after impact; this is unphysical and in effect increases the gradient of the ramp wave produced in the simulation. Increasing the erosion parameter was found to greatly improve the agreement. However this had the disadvantage of rendering the simulation more vulnerable to mesh tangling issues, particularly for the higher velocity impacts. This resulted in truncated modelling runs due to a tangled mesh causing the timestep to collapse. Work to overcome this issue is ongoing. Despite the truncation, good agreement can be seen between the experimental and modelled datasets, particularly for the high velocity shot.

![Figure 5](image.png)

**Figure 5.** Comparison of selected experimental and modelling data for 5 mm spike height flyer system; (a) shows particle velocity comparison for 536 ms\(^{-1}\) impact and (b) the shock pressure comparison for 957 ms\(^{-1}\) impact. Trace labels indicate the distance of the gauge element relative to the target/buffer interface (mm).

### 6. Future Work
Future experiments will be carried out with different flyer designs that will aim to produce a shorter duration ramping wave followed by a sustained shock (before release effects occur). Additionally Het-v/PDV diagnostics will be used to validate the output from the particle velocity diagnostics. Additional experiments to measure the CSL manufactured ceramic EOS, strength and failure parameters will also be carried out to further inform the computer modelling.

### 7. Conclusions
A novel ceramic flyer ramp wave generation method has been trialled and shockless compression loading paths leading to a shock wave have been produced; in addition, good agreement has been obtained between experimental and modelling results. Further experiments will apply this novel loading technique to energetic targets.

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